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HIGHWAY RESEARCH REPORT

INVESTIGATION OF ROCK SLOPE PROTECTION MATERIAL

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STATE OF CALIFORNIA

TRANSPORTATION AGENCY

DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

NO. M & R 632561

Prepared in Cooperation with the U.S. Department of Commerce, Bureau of Public Roads April 1967

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State of California
Department of Public Works
Division of Highways
Materials and Research Department

April 21, 1967

Lab Auth 632561

Mr. J. C. Womack
State Highway Engineer
Division of Highways
Sacramento, California

Dear Sir:

Submitted for your consideration is:

INVESTIGATION

of

ROCK SLOPE PROTECTION MATERIAL

Study made by .... Foundation Section
Under general direction of .... Travis Smith
Work supervised by .... M. L. McCauley
Report prepared by .... J. Gamble
R. Mearns

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

Attach

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Abstract

The use of rock slope protection material on highway construction projects in California has increased markedly in the last decade. Prior to this study severe deterioration of several installations in California was known, but there was little knowledge of the general performance of rock slope installations throughout the state. Inspection of numerous installations of varied age and rock type in all sections of the state, showed that only a few were constructed of poor quality rock. Consequently, failures due to rock disintegration are relatively rare. The weathering processes and their effect on rock slope installations are evaluated, and the conclusion is drawn that initially sound rock will be little affected by weathering during the design life of an installation.

Test records compiled since 1957 show wide discrepancies in correlation between the Specification test results and performance. An analysis of data from these records: (1) show that the Los Angeles Rattler test could be discontinued as a specification test since 97.6 percent of the samples that fail this test are rejected by at least one other test; (2) are the basis for recommending that the Sodium Sulfate Soundness test specification be raised from 5 percent to 10 percent maximum loss; and (3) indicate that the presently used 2.5 minimum Specific Gravity and 2.0 percent maximum Absorption specifications are reasonable values. The Standard Specifications do reject obviously poor rock, but they also reject much satisfactory material. This wide range in quality of rejected material is due in part to discrimination of the tests against some rock types.

A range of test values was set up and performance categories established so that correlations could be made between test results and performance. The Los Angeles Rattler test proved to be the poorest performance predictor. The Soundness test with a 10 percent maximum loss specification (as recommended) and the Absorption test were the best performance predictors. The results from each of the specification tests were in turn compared to the remaining three tests. This comparison disclosed that most rocks which pass Absorption and Soundness will also pass the Specific Gravity and Los Angeles Rattler tests. A study of the Absorption test method shows that particle size influences the values obtained. It is recommended that a standardized procedure for grading Absorption test samples be closely followed.

The Wet-Dry and Freeze-Thaw methods were evaluated by testing blocks, various particle sizes, and varying the test procedure. A quantitative test was not developed for either method. In addition, the long period of time required to run the tests is normally impractical in this department. Interestingly, sea

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water was found to be less severe than fresh water in the Wet-Dry test. The Durability test as now performed on coarse aggregate appears to be a useful performance indicator. A minimum Dc value of 60 is suggested by the available data but more testing is required before a specification can be recommended.

Considerable experimental testing was done to develop a simple and practical Rapid Abrasion test. The results correlate with performance and the method shows promise as a specification test but more developmental testing is required. Finally, two index formulas were devised that yield index numbers which are related to performance. Both formulas are significantly better performance predictors than the present specifications.

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INVESTIGATION of ROCK SLOPE PROTECTION MATERIALS

Introduction

Purpose and Scope

As highway construction projects in California increase in magnitude and cost, the need for satisfactory bank and slope protection also increases. Figure 1 shows the number of rock slope protection samples submitted for testing to the Materials and Research Department each year since 1956. The rapid increase in the number of samples being tested clearly indicates the increasing importance of rock slope protection material on California Highway Projects. A study of the standards of quality

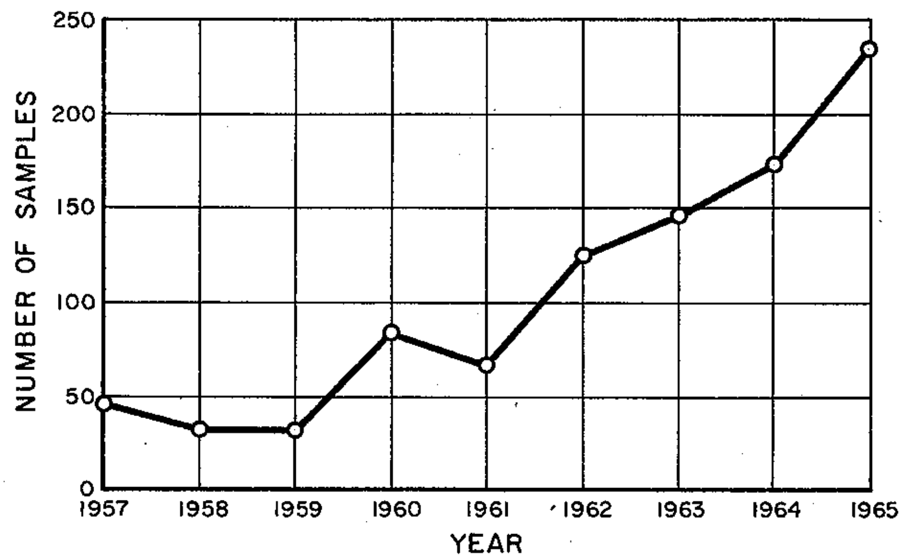

Figure 1.-Rock Slope Protection Samples Submitted to the Materials and Research Department

used to select rock for slope protection, and of the utilization and performance of this material, is especially germane at this time.

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The purpose of this investigation was fourfold: (1) to determine the prevalence and causes of rock failure on existing installations; (2) to determine how results of the present specification tests are related to the performance of a material on an installation; (3) to recommend changes of the specification limits and procedures that will improve the ability of these tests to predict how rocks will perform on an installation; and (4) to investigate new test methods.

The ability of the specification tests to consistently accept rock suitable for slope protection material and reject unsuitable rock has long been questioned. The magnitude of this problem is indicated by the numerous exceptions to the Standard Specifications which are approved either to permit use of a material known to be satisfactory, or to permit use of a local material for economic reasons. Since only a limited study of the relation between test results and field performance had been previously made, there was no rational way this problem could be remedied. The present study furnished data upon which recommendations could be reliably based.

Prior to this study, the rapid disintegration of rock on several large installations in California was known, and at Waddell Bluffs this condition was intensively studied. However, the prevalence of rock disintegration on installations throughout the State was largely unknown. During the present investigation selected installations were examined in every section of the State, and additional installations were found on which the rock was disintegrating. However, only a relatively few installation failures caused by poor rock quality were observed and the rock used on these installations would be rejected by the present specifications. It was observed that most installation failures were caused by inadequate design or poor construction methods or a combination of both.

Although a considerable amount of test data had been accumulated on rock slope protection material before the present study was undertaken it was not in a form that could be analyzed. Some type of convenient data storage and retrieval system was a prerequisite to further study and the attendant gathering of additional data. An edge-punch data retrieval card file system was set up and has served very well.

Finally, the acquisition of an X-ray diffractometer by the Materials and Research Department Laboratory affords a new and rapid means of making reliable identifications of the clay and secondary minerals. Thus far much of the X-ray work has necessarily been experimental and directed towards standardizing the techniques of semi-quantitative mineral identification. Nevertheless, a number of useful identifications were made of some rocks that were studied.

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Acknowledgments

The Foundation Section of the Materials and Research Department conducted this study. The work was done under the 1964-66 Work Program HPR-1(2) D-5-3 in cooperation with the U.S. Department of Commerce, Bureau of Public Roads.

Recommendations

Recommendations resulting from this study are listed below:

A. Standard Specifications

1. Discontinue the Los Angeles Rattler as a Specification test for rock slope protection material.

2. Raise the specification limit of the Sodium Sulfate Soundness test to 10 percent maximum loss.

B. Test Procedures

1. Use a 4000± gram sample of 1 x 3/4 inch material only in performing the Sodium Sulfate Soundness test.

2. Blend 2500± grams each of 1½ x 1 inch and 1 x 3/4 inch materials when preparing samples for the Absorption test.

C. Further Study

1. Gather data to determine a specification based on the Durability test for coarse aggregate.

2. Study the development of the Rapid Abrasion test.

3. Gather data for evaluation of the Index Formulas.

4. Gather data to determine relationships between rock types, performance and environment.

Two recommendations which are not included in the above categories are: (1) make a thorough study of the material before modifying or waiving the Standard Specifications and (2) make greater use of the petrographic, D.T.A., and X-ray diffraction methods in evaluating materials.

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Summary

The specifications for rock slope material used by the California Division of Highways were originally developed for concrete aggregate and later modified for rock slope protection material. The tests now in use to determine the quality of rock for slope protection are Sodium Sulfate Soundness, Los Angeles Rattler (LART), Apparent Specific Gravity, and Absorption.

Our study shows wide discrepancies in correlation between test results and performance records which indicate some of the test methods or specification limits, or both, are not appropriate for testing rock slope protection material.

The test results and service records show that the material used on 41 percent of the installations that were evaluated failed one or more of the specification tests, but that only 12 percent of these installations had unsatisfactory service records that could be related to the material. Although the age of the installations vary, we believe the above figures show that the specification tests reject substantial amounts of material that could be used successfully for certain kinds of rock slope installations.

As part of this study, materials were classified in one of four broad rock classifications: intrusive; volcanic; metamorphic; and sedimentary. Also each of the installations which were evaluated were placed in one of four environment categories: marine; inland wet; inland dry; and inland wet and dry. No relationship between rock classification and performance in any environment was detected. Additional data will be required to determine if any correlation exists.

A comparison of the results of various tests with performance shows LART has the poorest correlation; the Soundness test with 10 percent maximum loss (see p. 16) and the Absorption test have the best correlation. The other tests evaluated as predictors of performance, listed in order of decreasing reliability, are: Durability, Rapid Abrasion, and Apparent Specific Gravity.

Two formulas were developed for combining test results to yield an Index Number. Both formulas are superior to the present specifications for predicting performance, and one formula (the Durability Absorption Ratio) has the additional advantage of using tests that can be performed by the Highway Districts thereby saving considerable shipping and testing costs.

The Sodium Sulfate Soundness test is primarily an accelerated mechanical weathering test that determines the resistance of a rock to slaking and/or fragmenting under stresses caused by crystal growth in the voids. Poorly cemented arenaceous, argillaceous, or finely fractured rocks sustain high loss in the test. The test results do not reflect the adverse effect caused by widely spaced fractures since they are destroyed by the crushing process. How-

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ever, crushed rock fragments have greater losses than 3-inch cubes; this is attributed to the greater angularity and surface area in the sample of crushed fragments. The Soundness test results vary consistently with rock type, e.g., granitic and metamorphic rocks have lower losses than volcanic rocks, but most sedimentary rocks have higher losses. About 70 percent of all samples tested pass the 5 percent maximum specification limit. The percentage of samples that pass the Soundness test ranges from 86 percent for granitic rocks to 50 percent for sedimentary rocks.

The 5 percent Soundness specification, frequently modified or waived by the Districts to permit use of more economic material, does not seem equally applicable to all types of rock. It also does not correlate well with performance.

A Soundness specification of 10 percent maximum loss gives a closer correlation with performance, reduces the severity of the test method, and aids in reducing the discrimination against sandstones. For these reasons a specification change from 5 to 10 percent maximum loss is recommended.

Our data substantiates the findings of Drew and Woods (1960) that the Los Angeles Rattler test is not appropriate for testing rock slope protection material. The data show that of 622 samples tested, only 2.4 percent failed the Rattler test without also failing one of the other specification tests. Eleven of the fifteen samples that failed only the Rattler test were granitic rocks, and four of these were from installations with successful service records. This test is more severe for granitic rock types than for non-granular rocks such as basalt or schist.

Because the LART rejects very few samples that are not rejected by other specification tests and because some of the rejected samples have satisfactory service records, it is recommended that the LART be discontinued as a Specification test.

The 2.5 minimum apparent Specific Gravity specification is easily met by most rock slope protection material submitted to the laboratory. Ninety-one percent of 698 samples tested passed this specification. Granitic and metamorphic rocks rarely fail the test; 88 percent of 220 sandstones, and 81 percent of 112 volcanic rocks passed the test. This test, although it does not correlate well with performance, prevents the use of light weight rock which is undesirable for most installations.

The Absorption test as now performed can give different values for the same material. The numerical value of the specification limit is small and variations in the results that are due to variations in test procedure must be kept to a minimum. It is recommended that a grading specification be developed for

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the sample and that such a specification be included in the test method*. Seventy-four percent of 698 samples tested passed the Absorption test. Nearly all of the granitic and metamorphic rocks (95% and 90% respectively), 63 percent of the Sandstones, and 43 percent of the volcanic rocks passed this specification.

An analysis was made that compared the percent of samples that passed or failed any one of the four specification tests to the percent of samples that passed or failed each of the other three tests.

Comparison of the Soundness test to the other three specification tests showed that most samples passed the other tests regardless of their performance in the Soundness test. However, only about half of the samples which fail Soundness, pass the Absorption test.

The Los Angeles Rattler test was compared in the same manner to each of the other tests. The analysis showed that LART results do not correlate well with Specific Gravity results, but duplicate to some extent the results of both the Soundness, and Absorption tests.

A direct relation was found to exist between Specific Gravity, Absorption, and Soundness, i.e., most samples that pass Specific Gravity also pass the Absorption and Soundness tests, and most samples that fail Specific Gravity also fail the other two tests. Interestingly, this same relation does not exist between Specific Gravity and the Rattler test, i.e., 92 percent of the samples that pass Specific Gravity do pass the Rattler, but 70.6 percent of the samples that failed Specific Gravity passed the Rattler test.

Comparing Absorption with each of the other three tests showed that most of the samples that pass the Specific Gravity and Rattler tests do so whether or not they pass Absorption. However, some correlation exists between Absorption and Soundness.

Limited data on the Durability test, previously used only as a Specification test for coarse aggregate, indicate the test is useful for determining the durability of rock slope protection material. An analysis of 225 test results suggests that a minimum Dc value of 60 would be a reasonable specification limit. The analysis also showed that 97.4 percent of the samples with a Dc value of 75 or greater will pass the Soundness test.

Considerable experimental testing was directed toward developing quantitative Wet-Dry and Freeze-Thaw tests, but without success.

*This change in test procedure has been made. A grading specification has been developed and the test method revised for April 3, 1967.

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The Wet-Dry test lacks severity and requires at least 15 days to complete. The deleterious effect of sea water in the Wet-Dry test as performed in this investigation was less than for tap water, and the use of wetting agents or increased wetting and drying times did not increase the percent loss.

In the Freeze-Thaw test only fractured or foliated rocks, or those with expansive minerals had significant losses; all of these rocks would have failed one or more of the Specification tests. Also, the results obtained from this test do not correlate with the results of any of the present Specification tests. An inherent disadvantage of the Freeze-Thaw test as performed in this study is that 33.3 days are required to complete 200 cycles. This is considered to be the minimum number of cycles necessary to adequately test the rock.

An experimental test method for quantitatively evaluating the abrasion resistance of rock was developed using commercial abrasives and rock tumbling techniques. Results obtained from this test method showed a better correlation with performance evaluations than either the LART or Specific Gravity tests. Although some research of the test method has been completed, additional study is needed to determine the proper specification limit. Because of the ease and speed of this test method and the relatively good correlation with field performance, it is recommended that this test method be developed for possible use as a specification.

Petrography, X-ray diffraction, and differential thermal analysis are used to determine the mineral composition, approximate percentages of some minerals, textural details, and rock classification. This data is of great value for predicting rock performance and cannot be obtained or inferred from the Specification test results. In this report no specifications are proposed for these methods. However, because of their usefulness for evaluating rock quality, it is recommended that greater use be made of these methods. Qualified and experienced personnel should be employed in performing these tests to assure maximum usefulness.

Previous Work

An earlier study of rock slope protection material by the Materials and Research Department was made by Eldridge D. Drew and H. D. Woods. Their investigation is covered in a report entitled "Deterioration of the Riprap at Waddell Bluffs, IV-SCr-56-C, and An Evaluation of Physical Tests as a Method of Determining the Durability of Stone for Riprap." Their report describes an investigation that was made to determine the cause for the disintegration of heavy stone riprap at Waddell Bluffs. The report also evaluates the specification tests for riprap in use at that time as well as several other test methods.

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Although this study of test methods included only granitic rocks, limitations of the specifications were recognized and specific recommendations were made. The report is dated February 25, 1952, and appears in a State of California publication "Bank and Shore Protection in California Highway Practice," published in 1960.

Weathering Processes

To perform adequately as rock slope protection, natural rock must remain intact on an installation for many years. To meet this longevity requirement the rock selected for use as slope protection must be resistant to chemical alterations that lead to early decomposition, and to physical forces peculiar to the local environment that tend to wear away, or break it into smaller fragments (disintegration). In addition, the rock used for slope protection must be able to resist excessive fragmentation in the loading, hauling, and placement operations required to move it from quarry to installation.

The natural chemical and physical processes that cause decay and disintegration of rock at or near the earth's surface are called weathering. The authors agree with Reiche (1950, p. 9) that in most natural environments chemical weathering is the most important of the two weathering processes. However, rock used for slope protection may be placed in a local environment where the physical processes are of primary importance. An example might be an installation that is required to withstand heavy wave action. To perform satisfactorily in this particular environment one of the properties the rock must have is high resistance to abrasion.

Among the more important chemical processes acting toward deleterious alteration of rock are hydration and hydrolysis, oxidation, base exchange, solution, reduction, and carbonation. The physical processes, according to Reiche (1950, p. 9) which cause essentially in situ fragmentation or comminuting without contributory chemical change are not more than five. These are: expansion consequent on unloading; thermal expansion; crystal growth, including frost action; colloidal plucking; and some aspects of organic activity. Two other processes that are not limited by the in situ definition of Reiche are the dislodging of grains by wind and wind-blown sand, and abrasion by stream and wave action.

Few quantitative values are known for the rate of rock weathering. However, it is a safe assumption that the alteration and eventual disintegration of an originally durable rock, requires a much longer time than the two or three decades that rock on an installation is normally expected to remain intact. The disintegration of rock that is infrequently observed on installations is, with few exceptions, the end result of chemical and physical weathering processes that began long before the rock was quarried. It seems likely that the process of alteration and

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decay may be greatly accelerated in some rocks when they are removed from their in situ environment to a new and different environment. Consider the case of a foliated moderately weathered granite from a desert environment being used on an installation in a wet marine environment. A small amount of montmorillonite (not uncommon in weathered granite) can cause very rapid disintegration of the already physically weakened rock. Although obviously not good rock slope material, this same rock may have given satisfactory service on a small installation in a dry climate.

The most suitable rocks for rock slope installations are fresh, durable, and free from shale or clay seams, thin bedding planes, closely spaced fractures and foliation planes, or other structural features along which the rock will split.

Sampling

It is axiomatic that test results can only reflect the physical properties of the material in the samples tested. In practice it is assumed that a relatively large volume of rock will have the same physical properties as the material in the samples that were taken from the larger mass. This assumption is valid only to the extent that the samples are truly representative of the entire rock mass from which they were taken.

Obtaining a representative sample may be a simple task in obviously unweathered homogeneous rock as occurs in some quarries. However, in quarries where complex structures, different rock types, alterations, and varying degrees and depths of weathering occur, obtaining a representative sample requires judgment and experience. Careful selection of material is necessary in quarries of this type. Newly opened quarries or quarries which have not been previously tested also require special attention to sampling until acquaintance with the material is gained.

The individual samples collected must consist of only one rock type. This is implied in the sampling instructions for ledge rock that appear in the Construction Manual (8-02.01a). The last paragraph of this section reads: "Separate samples of unweathered stone shall be obtained from all strata that appear to vary in color and structure." On occasion samples have been received at the Materials and Research Department laboratory that consisted of one, two, or more rock types. The test results from such a sample are difficult to evaluate, and the sample cannot be evaluated visually if the material is of mixed quality.

The foregoing discussion of sampling is intended to emphasize the influence of sampling on the test results and hence, on the quality of the material actually used on installations. The results obtained from even the most careful testing are of value only to the extent that the material tested is representative of the material actually used.

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Card File

A permanent card file has been established to provide convenient storage for data on rock slope protection samples submitted to the Materials and Research Department for testing. The file contains data on all samples submitted since January 1, 1957.

This set of data was obtained by determining certain physical properties of many kinds of rock. However, it is not representative of rocks in general, since obviously poor material and material which failed tests performed by the Districts is usually not submitted to this department for testing.

Initially the data was recorded on 3 x 5 inch cards. To facilitate statistical analysis of the data, an edge punch data retrieval system was incorporated into the file. Some preliminary analyses were made and the file system proved very useful. Subsequently, it was decided to use 5 x 8 inch cards in order to increase the quantity of data that could be recorded, and to increase the number of retrievable categories.

Figure 2 shows the card-form on which the data is recorded and also shows typical information copied from the Sample Identification Card (Form T-101) and the Record of Tests Card (Form T-200) which accompany the sample.

Figure 3 shows the index card for the data retrieval system. The categories of retrievable information and their position on the card are marked. Rock types and counties are number-coded to reduce the number of edge-punch spaces required. Room has been provided for expanding both the information on the cards and the number of retrievable categories.

No serious problems have been encountered in using the card file as it is presently set up, and many anslyses have been completed with a significant saving of time. The analyses described in this report were made on data from all samples submitted to this department between January 1, 1957 and June 30, 1965.

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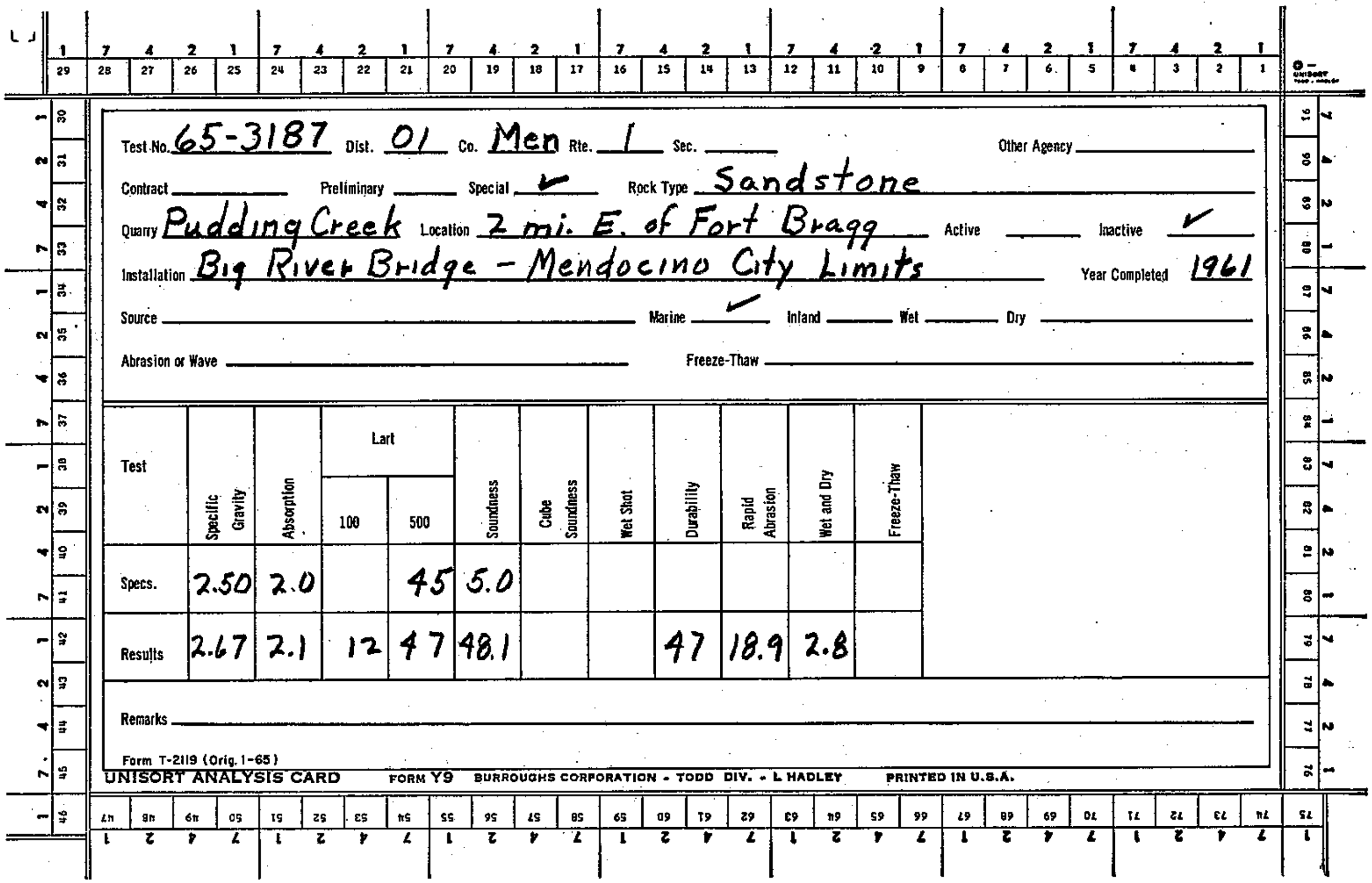

Test No. 65-3187 Dist. 01 Co. Men Rte. 1 Sec. ____ Other Agency ____

Contract ____ Preliminary ____ Special ✓ Rock Type Sandstone

Quarry Pudding Creek Location 2 mi. E. of Fort Bragg Active ____ Inactive ✓

Installation Big River Bridge - Mendocino City Limits Year Completed 1961

Source ____ Marine ✓ Inland ____ Wet ____ Dry ____

Abrasion or Wave ____ Freeze-Thaw ____

Test	Specific Gravity	Absorption	Lart 100	Lart 500	Soundness	Cube Soundness	Wet Shot	Durability	Rapid Abrasion	Wet and Dry	Freeze-Thaw
Specs.	2.50	2.0		45	5.0						
Results	2.67	2.1	12	47	48.1			47	18.9	2.8	

Remarks ____

Form T-2119 (Orig. 1-65)
UNISORT ANALYSIS CARD FORM Y9 BURROUGHS CORPORATION - TODD DIV. - L HADLEY PRINTED IN U.S.A.

Figure 2.-Typical File Card

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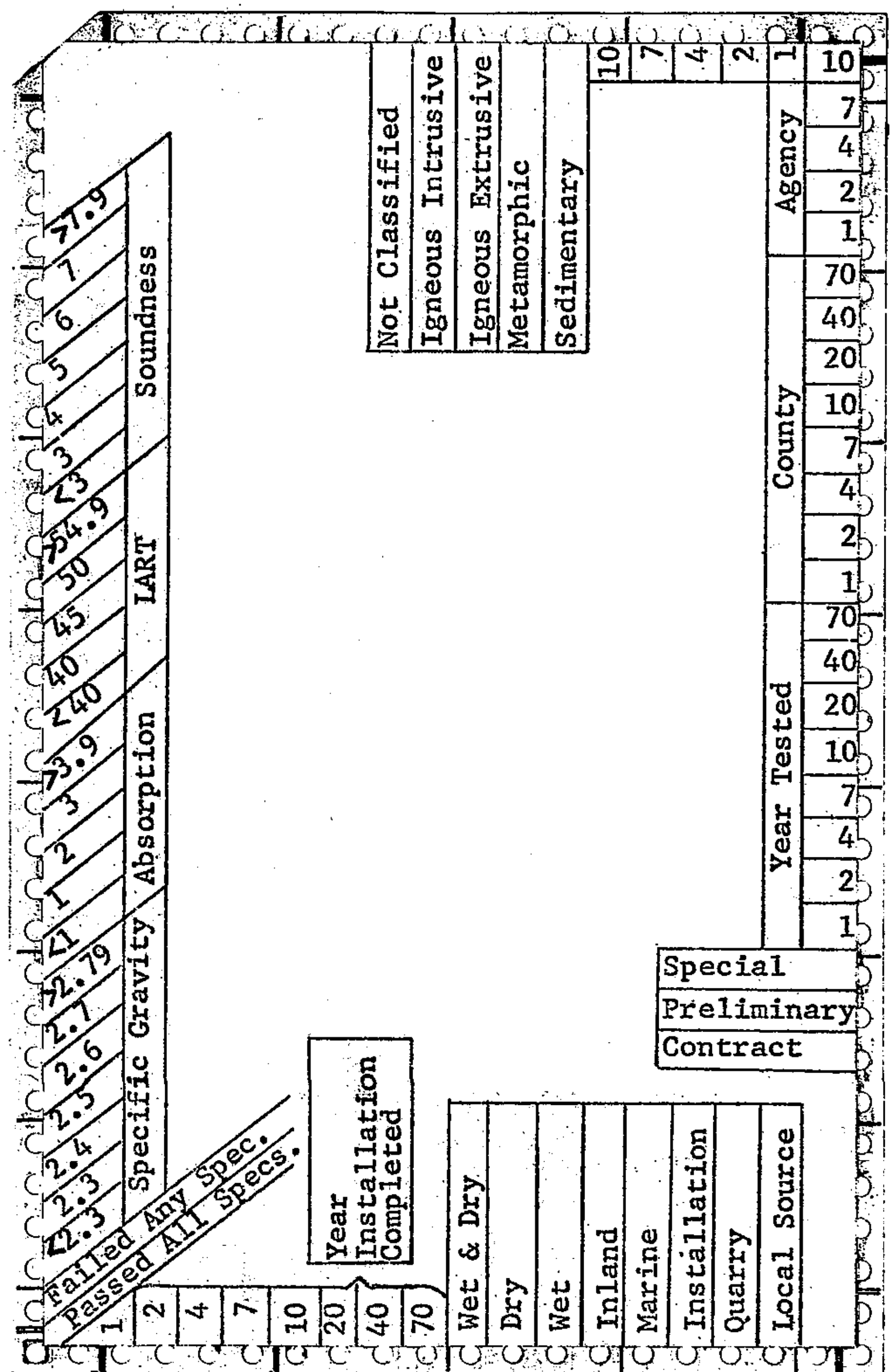

Figure 3.-Index File Card

Evaluation of Installations and Quarries

General

Collecting data on the actual performance of various rock types after they had been placed on installations was an important part of this investigation. In order to observe a wide range of rock types under various climatic conditions, and to assure inspection of any problem installations, it was decided to visit each of the eleven Highway Districts.

The installations and quarries visited were selected after consulting with District personnel, but the selections made were not limited to Division of Highways projects. Selections were based on such diverse factors as rock type, kind of environment, past performance of the rock, and quality of rock as determined by the specification tests.

All inspections were conducted by the authors to assure a uniform evaluation and to permit comparisons between the various locations. The inspections consisted of evaluating the rock quality and performance, photographing the installation or quarry, obtaining samples for testing whenever possible, and installing brass tags (see Appendix A) at certain locations.

A total of 72 installations and 25 source areas were inspected. Appendix B contains a map showing the locations of these installations and sources and a tabulation of pertinent data about each. Only 65 installations were considered satisfactory for sampling and testing and the data from these installations were used in the following analyses.

Performance Categories

The performance of the material on each of the 65 installations was rated by the authors as "very good," "good," "marinal" or "unsatisfactory." These performance categories were defined empirically by taking into account the following factors: hardness, shape, fractures, weathering, resistance to abrasion, and disintegration caused by secondary alteration. The age*, size, and environment of the installation, and the size of the blocks were not considered in rating the performance

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*The age of an installation per se is not considered a critical factor in the performance of sound rock. As discussed above on pages 8 & 9, rocks which are disintegrating on an installation were initially of poor quality, and their condition of failure cannot be attributed to the relatively short period of time they were on the installation. The inherent physical properties of the rock which cause failure are affected by the environment of the installation and failure may be accelerated. These physical properties were evaluated in making the performance ratings.

of the material. A rock, to be classified as "very good," must be hard, fresh, massive, equant, angular, and have a relatively high specific gravity. The degree of departure from one or more of these desirable characteristics determined the performance category in which each of the rocks was placed.

The number of installations in each performance category, and the number of installations in each category that fails to meet the 1964 specifications are shown in the table below. Non-

Category	No. of Installations	No. Failing Specifications
Very good	26	1
Good	26	14
Marginal	7	6
Unsatisfactory	6	6

specification material was used because of the common practice of waiving one or more of the specification requirements when the need arises. It appears that the 1964 specifications are too severe, and reject much satisfactory material. The table shows that only 56 percent of the non-specification material was satisfactory (very good or good categories). It is concluded that waiving specifications to compensate for their inability to correctly predict performance frequently results in the use of unsatisfactory rock slope material.

Rock Classification Versus Performance

Rocks on the 65 installations selected for study were placed in one of four broad rock classifications which could be compared with the performance of the rock both in the field and in the specification tests. Table 1 shows the results of these comparisons.

Table 1.-Number of rocks that pass or fail the 1964 Standard Specifications for each Classification and Performance Category.

	Performance Category									
Rock Classification	Very Good Pass	Very Good Fail	Good Pass	Good Fail	Marginal Pass	Marginal Fail	Unsatisfactory Pass	Unsatisfactory Fail	Total Pass	Total Fail
Intrusive	12	1	3	6					15	7
Volcanic	6		1	4	1	2		3	8	9
Metamorphic	4		3	1		1			7	2
Sedimentary	3		5	3		3		3	8	9

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No "marginal" or "unsatisfactory" intrusive rocks were found. While the present specifications apparently prevent the use of poor intrusive material, they also reject a significant number of "good" and "very good" materials. No intrusive rocks which failed either Specific Gravity or Absorption were found. Most of the intrusive rocks that do not meet specifications fail the Los Angeles Rattler test which discriminates against granular rocks.

Installations of volcanic rock are found in each performance category, but only those in the "very good" category consistently met specifications. One "good" and one "marginal" rock also met specifications. A high degree of correlation was found between Absorption and Soundness for volcanic rock. Most of the "marginal" and "good" rocks which failed specifications failed Absorption which suggests that the Absorption specification may be too low for this type of rock.

Although limited, the data in Table 1 suggests that the present specifications can be used to satisfactorily predict the performance of metamorphic rocks. The specification limits appear to be slightly conservative since the two failing metamorphic rocks failed by only a narrow margin and were performing satisfactorily.

Sedimentary rocks are represented in all of the performance categories. All "marginal" and "unsatisfactory" rocks fail one or more specification test but many of the "good" rocks also fail specifications. The present specifications appear to be adequate for eliminating poor sedimentary rock, but they also reject a significant number of "good" rocks.

Several marine installations on which two types of rock were used are located on the coast between Santa Barbara and Santa Monica. These installations are of special interest because here the performance of different rock types under the same conditions can be evaluated. A high quality granite was imported, and local medium to good quality sandstone, conglomerate, and volcanic rock was added to repair the installations. Some of these local rocks show signs of deterioration but others are performing well. The performance of each rock type under identical conditions agrees with the quality as determined by visual examination and test results.

Correlation of Performance with Test Methods

A series of calculations were made to determine how well the results of certain tests correlate with performance. The tests selected for this study included the Coarse Durability (p. 32) and the Rapid Abrasion (p. 43) as well as the specification tests (p. 20).

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To make these calculations it was first necessary to determine a range of test values for each test that defines each of the performance categories. These ranges, although determined somewhat arbitrarily, are based on considerable experience and the limiting values are considered reliable. The range of values selected for each test is shown in the table below:

Test	Very Good	Good	Marginal	Unsatisfactory
Specific Gravity	> 2.74	2.65-2.74	2.60-2.64	< 2.60
Absorption	< 0.8	0.8 -2.0	2.1 -2.5	> 2.5
LART	< 20	20-40	41-50	> 50
Soundness	< 1.0	1.0 -10.0	10.1-15.0	> 15
Durability	> 80	60-80	40-59	< 40
Rapid Abrasion	< 10.0	10.1-15.0	15.1-20.0	> 20

Using the values in the table, each material was assigned to the performance category indicated by the results of each of the tests. These performance ratings were then compared with the actual field performance category of the material.

The following table shows the percent of correct evaluations by each of the tests in each of the performance categories:

Test	No. of Samples	Correct Performance Predictions (%)				
		Very Good	Good	Marginal	Unsatis-factory	Weighted Average
Sp. Gr.	65	65	65	0	17	54
Absorption	65	73	65	14	67	63
LART	65	38	58	29	33	45
Soundness	64	52	81	14	100	63
Durability	60	43	83	14	67	58
Rapid Abrasion	54	57	60	43	50	56

In general, the table shows that the LART is the poorest performance predictor, and that the Soundness and Absorption tests are the best predictors. Durability, Rapid Abrasion, and Specific Gravity are only mediocre performance predictors.

Index Formulas

Since each of the above tests measure different properties that contribute to rock quality, an attempt was made to combine test results in a formula which would yield an index number directly related to performance.

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No "marginal" or "unsatisfactory" intrusive rocks were found. While the present specifications apparently prevent the use of poor intrusive material, they also reject a significant number of "good" and "very good" materials. No intrusive rocks which failed either Specific Gravity or Absorption were found. Most of the intrusive rocks that do not meet specifications fail the Los Angeles Rattler test which discriminates against granular rocks.

Installations of volcanic rock are found in each performance category, but only those in the "very good" category consistently met specifications. One "good" and one "marginal" rock also met specifications. A high degree of correlation was found between Absorption and Soundness for volcanic rock. Most of the "marginal" and "good" rocks which failed specifications failed Absorption which suggests that the Absorption specification may be too low for this type of rock.

Although limited, the data in Table 1 suggests that the present specifications can be used to satisfactorily predict the performance of metamorphic rocks. The specification limits appear to be slightly conservative since the two failing metamorphic rocks failed by only a narrow margin and were performing satisfactorily.

Sedimentary rocks are represented in all of the performance categories. All "marginal" and "unsatisfactory" rocks fail one or more specification test but many of the "good" rocks also fail specifications. The present specifications appear to be adequate for eliminating poor sedimentary rock, but they also reject a significant number of "good" rocks.

Several marine installations on which two types of rock were used are located on the coast between Santa Barbara and Santa Monica. These installations are of special interest because here the performance of different rock types under the same conditions can be evaluated. A high quality granite was imported, and local medium to good quality sandstone, conglomerate, and volcanic rock was added to repair the installations. Some of these local rocks show signs of deterioration but others are performing well. The performance of each rock type under identical conditions agrees with the quality as determined by visual examination and test results.

Correlation of Performance with Test Methods

A series of calculations were made to determine how well the results of certain tests correlate with performance. The tests selected for this study included the Coarse Durability (p. 32) and the Rapid Abrasion (p. 43) as well as the specification tests (p. 20).

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To make these calculations it was first necessary to determine a range of test values for each test that defines each of the performance categories. These ranges, although determined somewhat arbitrarily, are based on considerable experience and the limiting values are considered reliable. The range of values selected for each test is shown in the table below:

Test	Very Good	Good	Marginal	Unsatisfactory
Specific Gravity	> 2.74	2.65-2.74	2.60-2.64	< 2.60
Absorption	< 0.8	0.8 -2.0	2.1 -2.5	> 2.5
LART	< 20	20-40	41-50	> 50
Soundness	< 1.0	1.0 -10.0	10.1-15.0	> 15
Durability	> 80	60-80	40-59	< 40
Rapid Abrasion	< 10.0	10.1-15.0	15.1-20.0	> 20

Using the values in the table, each material was assigned to the performance category indicated by the results of each of the tests. These performance ratings were then compared with the actual field performance category of the material.

The following table shows the percent of correct evaluations by each of the tests in each of the performance categories:

		Correct Performance Predictions (%)				
Test	No. of Samples	Very Good	Good	Marginal	Unsatis-factory	Weighted Average
Sp. Gr.	65	65	65	0	17	54
Absorption	65	73	65	14	67	63
LART	65	38	58	29	33	45
Soundness	64	52	81	14	100	63
Durability	60	43	83	14	67	58
Rapid Abrasion	54	57	60	43	50	56

In general, the table shows that the LART is the poorest performance predictor, and that the Soundness and Absorption tests are the best predictors. Durability, Rapid Abrasion, and Specific Gravity are only mediocre performance predictors.

Index Formulas

Since each of the above tests measure different properties that contribute to rock quality, an attempt was made to combine test results in a formula which would yield an index number directly related to performance.

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The Absorption and Durability tests were selected for use in such a formula because these tests can be performed by the Districts, thus saving the time and expense of sending samples to the Materials and Research Laboratory. The LART and Specific Gravity tests were not considered for use because of their poor correlation with actual performance. It was hoped that by equating the influence of each test and combining them in some manner, the resulting formula would yield an index number that could be used to select or reject rock slope protection material without further testing. The following ratio was devised to obtain such an index number:

$$\frac{(Dc)}{(Abs+5)} \times (K) = \text{Durability-Absorption Index}$$

$$K = 5.83$$

It is proposed that this index number be called the Durability-Absorption Ratio. The value of the constant K is such that when Dc = 60 and Absorption = 2.0% the ratio will equal 50$\pm$ 0.1. Thus, satisfactory rocks will have Durability-Absorption ratios greater than 50 and unacceptable rocks will have ratios less than 50. Based on the available data, the index numbers can range from 2 for a very poor rock to 109 for an exceedingly good rock. The ratios for "good" and "very good" rocks taken from 47 installations ranged in value from 37 to 94: the one sample having the failing index number of 37 was a volcanic rock that had high absorption. The "marginal" rock category has two samples with satisfactory indices and the "unsatisfactory" rock category has only one sample with a satisfactory index. These limited results encourage the belief that the Durability-Absorption Ratio can be used to discriminate between acceptable and unacceptable rocks, with the limitation that further study is required for those rocks that have index values between 35 and 55.

Extending the index number concept, the following equation was written:

$$\frac{(100\text{-Sound.})}{(1000\text{-}2\ Dc)} \times \frac{(Sp.\ Gr. + 2)}{(2\ Abs.) + 40} \times (100 - \text{Rapid Abrasion})(K) = \text{Rock Quality Index}$$

$$K = 53.25$$

It is proposed that this index number be called the Rock Quality Index (RQI). The constant K fixes the index number at 50$\pm$ 0.1 when the specification values for each test are substituted in the equation (values of 60 and 15 are assumed for the Durability and Rapid Abrasion tests respectively and 1964 Standard Specification limits are used for the other tests). The equation is balanced so that the influence of each test on the obtained index number is approximately equal. The index number ranges in value from 7.73 for a very poor rock to 83.34 for an exceedingly good rock. This range was obtained by arbitrarily

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using test values that are beyond the range of those obtained from most rocks. Forty-one rocks taken from installations in the "good" and "very good" performance categories have index numbers that range in value from 46.32 to 72.31. Only two of these rocks have index numbers below 50.

The table below shows the percentage of correct performance predictions for the index formulas and for the present Standard Specifications. To determine the percent of correct predictions for the index formulas the unsatisfactory and marginal rocks have index numbers less than 50; the good and very good rocks have index numbers greater than 50.

		Correct Performance Predictions (%)		
	No. of Samples	V and G	M and U	Weighted Average
Dc-Abs. Ratio	60	98	77	93
R.Q.I.	54	95	82	93
Present Specs.	64	71	92	75

On the basis of available data the index numbers are significantly better performance predictors than the present specifications. The practical value of the index numbers obtained from the Durability-Absorption Ratio and the Rock Quality Index cannot be fully known until more experience is gained in their use.

Environment

Although environment was not considered in evaluating the performance of material on an installation, it was described for each of the installations evaluated in the field. Four general environment categories were used: "marine," "inland wet," "inland dry" and "inland wet and dry." "Marine" environments are those along the ocean, "inland wet" installations are wet most of the time, and "inland dry" are dry most of the time. "Inland wet and dry" installations are wet about half of the time.

Each of the rock classifications are found in all environment categories with one exception -- no metamorphic installations in a "marine" environment were evaluated.

Because of limited data no definite conclusions could be reached. However, certain conditions were noted and further investigation may prove of value.

Most of the "very good" installations are "inland dry," suggesting that rocks may deteriorate more slowly with rare or intermittent wetting. It may also be true that lower quality rock can be used satisfactorily in a dry environment.

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There is no evidence in the study that a "marine" environment is significantly more severe than any other as far as causing disintegration of the material. Wave action does increase abrasion loss and some opening of fractures due to wave impact, but in general a "good" or "very good" rock on an inland installation will also be "good" or "very good" on a "marine" installation.

No relationship between rock type and performance in any given environment was noted, suggesting that environment does not discriminate against any of the four rock classifications which were used. However, further study is needed to determine the relationship between rock type, performance and environment.

Economic Factors

Economics was another factor that was not included in our evaluation of performance. A comprehensive discussion of economics would be very complex and beyond the scope of this report. The following discussion includes thoughts that were developed during this study.

Some installations were built entirely of friable rapidly disintegrating tuffaceous rock, and several were built with mixed good and poor material. These installations predictably provide poor protection.

The failure of a small installation by the relatively slow process of rock disintegration may be of minor consequence, but failure of a large installation by the same process could result in great economic loss. This loss may include not only the installation itself, but the embankment or structure it is protecting. The size of an installation then can be a factor in determining the durability of rock required to economically construct an adequate installation. Some installations may be constructed and maintained more economically by using non-specification local material than by importing specification material.

In some areas, the quantity of good material is limited and rock suitable for large installations is not available. The coastal region of Mendocino County is cited as one area where good quality rock of large size must be imported.

In practice, specifications for rock slope protection material are frequently changed or waived to permit use of local materials. For large permanent installations, a thorough study of the material should be made before changing or waiving of specifications is considered.

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Specification Tests

General

A search through old editions of the California Division of Highways Standard Specifications revealed that in the January 1930 edition there were no specification tests for riprap. The next edition, January, 1935, list the following specification tests: Specific Gravity - 2.5; Wet Shot Rattler - 37% max. loss; Los Angeles Rattler - 37% max. loss. With one exception (maximum loss in the Los Angeles Rattler test was raised to 40% in the July 1940 edition) these test specifications remained unchanged until 1960. In the January 1960 edition of the Standard Specifications the specification tests for rock slope protection material were:

Apparent Specific Gravity	2.5 min.
Absorption	2% max.
Soundness	5% max. loss
Wet-Shot Rattler	40% max. loss
Los Angeles Rattler	45% max. loss

In the July 1964 edition (in current use) the Wet-Shot test was dropped but otherwise the specification tests remain unchanged.

In addition to the four specification tests, rock used for riprap must conform to the following shape restrictions: (1) rock shall be of such shape as to form a stable protection structure of the required section; (2) rounded boulders or cobbles shall not be used on slopes steeper than 2 to 1; (3) flat or needle shapes will not be accepted unless the thickness of the individual pieces is greater than 1/3 the length.

The above summary indicates the numerous changes and modifications that have been made as the specification tests and their limits were developed.

The present study suggests that further adjustment of the specification tests are needed, and it shows that one of the present specification tests can be eliminated. New and perhaps more appropriate test methods are also suggested. The findings obtained from the present study of the specification tests are discussed below.

Sodium Sulfate Soundness Test

The Soundness test as performed at the Materials and Research Laboratory (Test Method No. Calif. 214-D) uses a saturated solution of sodium sulfate in which to submerge the sample. The saturation and temperature of the solution is controlled so that crystal growth is assured. The test is designed to act as an accelerated mechanical weathering test and the results are a

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reflection of several physical properties. The most important of these properties is the nature of the voids into which the solution can penetrate and initiate the growth of crystals. The rate of penetration, the absorption, the surface area of particles in the sample, and the nature of any fractures or joints are all related to this property. The presence of an expansive clay is an important property which influences the test results. Some other less important properties which may influence the test results are differential thermal expansion, chemical reactions between constituent minerals and the solution, and particle configuration.

As now determined, the percent loss in the Soundness test is calculated by averaging the losses from two samples of the same material. One sample is 3000 grams of 1½ x 1 inch crushed rock, the other is 1500 grams of 1 x 3/4 inch crushed rock. Analysis of past test results indicate that use of a 4000 gram sample of 1 x 3/4 inch crushed rock particles would be a more satisfactory procedure. This change in the test method is therefore recommended.

An inherent disadvantage of the Soundness test is that at least ten days are required for completion.

From their study of granitic rocks Drew and Woods (1960, p. 384) made a tentative recommendation of 5 percent maximum loss for riprap in the Soundness test. They clearly recognized the need for experimental testing with other rock types before establishing a specification limit. However, the tentative 5 percent specification was adopted and has been in use since 1960.

Numerous requests from the Districts for waivers of the Soundness specification cast doubt on the validity of the 5 percent limit. The study of rock slope installations indicates that a Soundness specification of 10 percent loss will correlate more closely with actual performance.

An analysis of 785 Soundness test results from all rock slope protection samples submitted to the Materials and Research Department from January 1, 1957 through June 30, 1965 shows that the Soundness test is the most severe of the specification tests, rejecting 30 percent of all samples tested.

The 5 percent Soundness specification appears to discriminate against sandstone. Fifty percent of all sandstones tested failed to meet specifications while only 14 percent of the granitic rocks failed. Additional analysis showed that only 27 percent of the samples tested were sandstone but nearly half of the failing samples were sandstone.

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Since the 5 percent loss specification was developed for granitic rocks and does not seem to apply to all other rock types, and since the correlation between this specification and performance is not too great, it is recommended that the specification be raised to 10 percent maximum loss. Use of this higher specification limit and the larger sample of one size of aggregate will improve quality control, improve reproducibility of the test method, and reduce the amount of testing required.

A histogram showing the distribution of test results obtained in the Soundness test was made for all of the samples submitted to the Materials and Research Department for Soundness testing from January 1, 1957 through June 30, 1965. Additional histograms were made for each of the four major rock classifications described on Page 14 of this report. These histograms are included in Appendix C.

The histograms show above average results for granitic and metamorphic rocks, average results for volcanic rocks and substantially lower than average results for sedimentary rocks.

One phase of our evaluation of the Sodium Sulfate Soundness test investigated the difference between samples composed of crushed rock particles and samples composed of 3 inch cubes sawed from a representative rock. The identical procedures were used on each type of sample and the percent weight loss was calculated using the weight of material which passes the half-size sieve, i.e., for the 3 inch cube a 1½ inch sieve opening was used, for 1½ x 1 inch crushed aggregate a ½ inch sieve opening was used, and for 1 x 3/4 inch crushed aggregate a 3/8 inch sieve opening was used.

Since 1961, 140 tests have been performed to compare test results from the regular Soundness test with test results from the cube Soundness test. Results of these tests are tabulated in Appendix C. Many different rock types from virtually all areas of the State were represented in this comparison study.

Analysis of data from this study shows that no direct relationship exists between results on the two types of tests. The way in which the material breaks down appears to be different for each test. The cube samples nearly all broke on pre-existing fractures with only minor surface plucking. Crushed material is apparently better than the original material. In crushing material, the pre-existing fractures are destroyed and loose or poor material is removed by the screening process. A study of the data shows that the highest loss recorded in the regular test was only 54.7 percent while in the cube test it was 100 percent. This also indicates the higher quality of the crushed material.

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Despite this apparent higher quality of material the regular test rejected 46 of the samples, while the cube test rejected only 25 samples. These rejections are based on the present specification of 5 percent maximum loss. The significantly greater surface area in the crushed aggregate sample multiplies the effect of surface plucking and permits regular Soundness losses to be greater than the cube Soundness losses. The effect of an increased surface area is readily apparent when the results of tests on the two sizes of crushed rock particles used in the Soundness test are compared. The material and test method are the same and only the particle and sample sizes are different, yet 92 percent of all samples tested show the 1 x 3/4 inch sized crushed rock to have more loss in the Soundness test than the $1\frac{1}{2}$ x 1 inch sized crushed rock.

The cube test has been discontinued because it does not correlate with the regular Soundness test which can be used successfully to predict performance, and because the results are really representative of only the rock from which the cube was cut.

Los Angeles Rattler Test (LART)

This test (Test Method No. Calif. 211-C) has long been relied upon to determine the abrasive resistance and durability of concrete aggregate, and since 1935, of rock slope protection material. Drew and Woods (1960, p. 377) in their study of physical tests as a method of determining the durability of stone riprap, found the test unsatisfactory as the sole means of judging the "probable behavior" of revetment stone. This was true, they thought, because the test was designed to test aggregates, not stone block, and it did not measure the resistance of rock to chemical weathering. They also found the Rattler test results were incongruous with the performance records of some well-known granitic rocks, i.e., some granitic rocks with excellent service records fail the Rattler test while some with poor service records pass. In commenting on this same report the Committee on Bank and Shore Protection (1960, p. 386) recommended that the Rattler test be replaced as a criterion for revetment stone. It is to be noted that this recommendation was made without benefit of the accumulated data now available and before the Absorption and Sodium Sulfate Soundness tests were added to the Standard Specifications.

New evidence that the Los Angeles Rattler test is inappropriate for determining the suitability of stone riprap is disclosed by test records compiled during the present study. Analysis of results of the present specification tests on all samples submitted to the Materials and Research Department from January 1, 1957 through June 30, 1965 showed that only 15 (2.4%) of the 622 samples tested failed the Rattler test without failing one of the other specification tests. Of these 15 samples eleven were granitic rocks, two were dolomite,

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one was andesite, and one a calcareous sandstone. Four of the granitic samples were taken from "good" installations. (See Table 10, p. 77).

Histograms were made that show the distribution of test results obtained in the Los Angeles Rattler test. The histograms drawn for the four different rock classifications show superior performance for metamorphic rock in the Rattler test, slightly above average for volcanic rock, and below average performance for sedimentary and granitic rocks. The histograms are included in Appendix D.

The above analyses show that the Rattler test could be discontinued as a specification test for rock slope protection material without significantly reducing quality control since 97.6 percent of the samples that fail this test are rejected by at least one other test. They also show that it is more difficult for granitic rock, and to a lesser degree sandstone, to pass the Rattler test than for nongranular rock types such as basalt or schist. This is probably a reflection of the predominant impact characteristic of this so-called abrasive test. On the basis of these findings it is recommended that the LART be discontinued as a specification for rock slope protection material.

Apparent Specific Gravity

The 2.5 minimum Specific Gravity specification for rock slope protection material has not been changed since its initial introduction in 1935. The test method (Test Method No. Calif. 207-D) is the same as that used for coarse aggregate, and is well standardized. Ninety-one percent of all samples of rock slope protection material submitted to the Materials and Research Department from January 1, 1957 through June 30, 1965 comply with the present specifications.

The elimintation of otherwise good material in order to obtain the advantage of slightly heavier material does not seem justified although this high percentage of acceptance suggests that the limit might be raised to a higher value. The percent of sedimentary, volcanic, granitic, and metamorphic rocks that pass the Specific Gravity test is shown in the histograms in Appendix E.

Absorption

The specification for Absorption is 2 percent maximum, and this seems to be a reasonable and practical limit for the test. Seventy-four percent of all samples tested from January 1, 1957 through June 30, 1965 passed this specification.

The range of Absorption values obtained for all samples, and for sedimentary, volcanic, granitic and metamorphic rocks is shown by the histograms in Appendix F. The tabulation below gives the percent of each of the four rock types that pass the specification:

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Sedimentary	63%
Volcanic	43%
Granitic	95%
Metamorphic	90%

These figures show that as a class, volcanic rocks fail the Absorption specification much more frequently than the other rock types. This is due in part to the vesicularity of many volcanic rocks, a condition that does not necessarily preclude good performance. An analysis of volcanic rocks used on the 65 installations studied, shows that those which failed only the absorption test performed "very good" or "good." The volcanic rocks that failed both the Absorption and Soundness tests were all in the "marginal" or "unsatisfactory" categories. The conclusion is drawn that volcanic rocks should not be rejected solely because they fail to meet the 2 percent absorption limit.

The Absorption test (Test Method No. Calif. 207-D) as performed on rock slope protection material is identical to the Absorption test for coarse aggregate. The test procedure does not specify the grading to be used so that grading variations are possible between different samples. (See footnote, p. 6). A study made to determine what effect different grading might have on the absorption values obtained is described below.

In the Absorption test, the exact relationship between surface area and test results is not clear. Values for absorption include both true absorption and surface capacity. The true absorption of a material should not vary with the size of the particles, but the surface capacity is entirely dependent on surface area.

Five materials were tested to determine the influence of surface area on values of absorption. Personnel of the Engineering Geology unit obtained the materials from various installations. Five rock types are represented. The materials were first tested using the routine procedures for preparing and testing rock slope protection materials. Then 5000$\pm$ gram samples of 1½ x 1 inch material were submitted for testing. After completion of tests on these samples, the material was crushed and the 3/8 inch by No. 4 fraction was retested for absorption. Results of all tests are included in the following table. In all cases the measured value of absorption for the fine material was significantly higher than for the coarse material.

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Table 2.-Influence of Particle Size on Absorption Values

Sample No.	Location	Rock Type	Regular Absorp.	$1\frac{1}{2}$"x 1" Absorp.	3/8"x#4 Absorp.
64-3483	North Yuba River Bridge	Schist	0.9	0.5	1.1
64-3484	Cave Rock, Nev. Lake Tahoe	Dacite	3.4	2.5	3.7
64-3486	Flycasters Bend near Truckee	Olivine basalt	3.2	2.8	3.3
64-3488	Truckee River & Squaw Creek	Tuff	1.9	1.7	2.2
64-4665	Davenport	Sandstone	2.0	1.1	2.3

Since particle size and hence surface area do influence the reported value of absorption, the method of sample preparation becomes important. There are no specific instructions on preparing rock slope protection samples for Absorption testing. Prior to the time of this investigation, samples were prepared by combining approximately 1250 grams of each of the following sizes, $1\frac{1}{2}$ x 1 inch, 1 x 3/4 inch, 3/4 x $\frac{1}{2}$ inch, and $\frac{1}{2}$ x 3/8 inch. If there were not enough of any given size the next finer size with extra material would be used to make up the difference. Using this procedure, it was possible for two samples of the same material to show both acceptable and unacceptable values of absorption in consecutive tests, depending on the availability of coarse and fine sizes in the sample. To prevent an occurrence such as this, samples are now blended with approximately 2500 grams each of the $1\frac{1}{2}$ x 1 inch and the 1 x 3/4 inch. It is still true however, that a shortage of either size may be compensated for by use of the other size.

Impartial and fair evaluation of rock slope protection material submitted for testing requires standardization of sample preparation methods on a State-wide basis. While screen size alone is not a direct measure of surface area, it can be used as a reasonable and practical approach to controlling the surface area of a sample. The use of exact weight of material retained on specific screen sizes for Absorption testing will increase the reproducibility of the test method and permit more useful and reliable comparisons between test results. (See footnote, p. 6).

Comparison of Specification Test Results

The tables and discussion on the following pages pertain to the comparison of each Specification test with each of the other Specification tests. The four Specification tests are Apparent Specific Gravity (Specific Gravity), Absorption, Los Angeles Rattler (LART), and Sodium Sulfate Soundness (Soundness). The comparisons are based on whether the sample passed or failed the present specifications for the tests being compared.

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Tables 3, 4, 5 and 6 show the number of samples which were used in making each comparison and the percentage of samples which fall into each category. The purpose of these comparisons was to determine if any of the specification tests were duplicating the results of any of the other tests.

In general these tables show that rocks which pass the Absorption and Soundness tests will usually pass the LART and Specific Gravity tests. This is further evidence that LART can be eliminated as a specification. Specific Gravity which correlates well with Absorption should not be eliminated because it prevents the use of light weight rock. Some correlation exists between Soundness and Absorption test results but it is not great enough to be useful.

With the exception of LART each of the present specification tests provide useful information about rock durability. For this reason no system of sequential testing* using just these tests was considered feasible. The most useful method of sequential testing developed during this investigation involves the use of the Durability-Absorption ratio. (See p. 17). These tests can be performed by the District laboratories and if the results are higher than 55 or less than 35 no additional testing would be required. If the results were between 35 and 55, the Soundness and Rapid Abrasion tests and a petrographic examination would then be required to evaluate the rock durability.

*Sequential testing as used here means performing only one test at a time with the need for subsequent testing dependent on the results of preceeding tests.

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Table 3.-Soundness Compared to Each of the other Specification Tests

Specific Gravity

Number of Samples	Percent		Percent of the Passing Soundness that		Percent of the Failing Soundness that	
	Passing Soundness	Failing Soundness	Passes Sp Gr	Fails Sp Gr	Passes Sp Gr	Fails Sp Gr
626	69.0	31.0	98.0	2.0	89.6	10.4

Absorption

Number of Samples	Percent		Percent of the Passing Soundness that		Percent of the Failing Soundness that	
	Passing Soundness	Failing Soundness	Passes Absorption	Fails Absorption	Passes Absorption	Fails Absorption
626	69.0	31.0	89.1	10.9	53.4	46.6

LART

Number of Samples	Percent		Percent of the Passing Soundness that		Percent of the Failing Soundness that	
	Passing Soundness	Failing Soundness	Passes LART	Fails LART	Passes LART	Fails LART
620	69.0	31.0	95.6	4.4	81.8	18.2

Sixty-nine percent of the samples in this comparison passed the Soundness specification. Most samples passed Specific Gravity and LART regardless of performance on the Soundness Test. Most samples also passed Absorption if they passed Soundness but only about 53 percent of the samples that failed Soundness passed Absorption.

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Table 4.-LART Compared to Each
of the Other Specification Tests

Specific Gravity

Number of Samples	Percent		Percent of the Passing LART that		Percent of the Failing LART that	
	Passing LART	Failing LART	Passes Sp Gr	Fails Sp Gr	Passes Sp. Gr	Fails Sp Gr
687	90.5	9.5	94.2	5.8	76.9	23.1

Absorption

Number of Samples	Percent		Percent of the Passing LART that		Percent of the Failing LART that	
	Passing LART	Failing LART	Passes Absorption	Fails Absorption	Passes Absorption	Fails Absorption
687	90.5	9.5	78.0	22.0	56.9	43.1

Soundness

Number of Samples	Percent		Percent of the Passing LART that		Percent of the Failing LART that	
	Passing LART	Failing LART	Passes Soundness	Fails Soundness	Passes Soundness	Fails Soundness
620	91.3	8.7	72.3	27.3	35.2	64.8

Approximately 91 percent of the samples in this comparison passed the LART specification. Most samples passed Specific Gravity regardless of the results of the LART test. Most samples that passed LART also passed Absorption and Soundness, while most samples that failed LART failed Soundness, and nearly half of the samples that failed LART failed Absorption. Apparently the Soundness and Absorption tests are duplicating to a significant extent the results of the LART.

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Table 5.-Specific Gravity Compared to Each of the Other Specification Tests

Absorption

Number of Samples	Percent		Percent of the Passing Specific Gravity that		Percent of the Failing Specific Gravity that	
	Passing Sp Gr	Failing Sp Gr	Passes Absorption	Fails Absorption	Passes Absorption	Fails Absorption
698	92.6	7.4	81.0	19.0	7.7	92.3

Soundness

Number of Samples	Percent		Percent of the Passing Specific Gravity that		Percent of the Failing Specific Gravity that	
	Passing Sp Gr	Failing Sp Gr	Passes Soundness	Fails Soundness	Passes Soundness	Fails Soundness
626	95.4	4.6	71.0	29.0	31.0	69.0

LART

Number of Samples	Percent		Percent of the Passing Specific Gravity that		Percent of the Failing Specific Gravity that	
	Passing Sp Gr	Failing Sp Gr	Passes LART	Fails LART	Passes LART	Fails LART
687	92.6	7.4	92.2	7.8	70.6	29.4

Approximately 93 percent of the samples in this comparison passed the Specific Gravity specification. Most samples which passed Specific Gravity passed Absorption, Soundness and LART. Most samples which failed Specific Gravity failed Absorption and Soundness. Apparently Soundness and Absorption duplicate the results of Specific Gravity to a significant extent. Most samples which failed Specific Gravity passed LART. This indicates Specific Gravity and LART do not correlate well.

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Table 6.-Absorption Compared to Each of the Other Specification Tests

Specific Gravity

Number of Samples	Percent		Percent of the Passing Absorption that		Percent of the Failing Absorption that	
	Passing Absorption	Failing Absorption	Passes Sp Gr	Fails Sp Gr	Passes Sp Gr	Fails Sp Gr
698	75.6	24.4	99.2	0.8	71.8	28.2

Soundness

Number of Samples	Percent		Percent of the Passing Absorption that		Percent of the Failing Absorption that	
	Passing Absorption	Failing Absorption	Passes Soundness	Fails Soundness	Passes Soundness	Fails Soundness
626	78.0	22.0	78.9	21.1	34.3	65.7

LART

Number of Samples	Percent		Percent of the Passing Absorption that		Percent of the Failing Absorption that	
	Passing Absorption	Failing Absorption	Passes LART	Fails LART	Passes LART	Fails LART
687	76.0	24.0	92.9	7.1	83.0	17.0

Approximately 76 percent of the samples in this comparison passed the Absorption Specification. Most samples which passed Absorption also passed Specific Gravity, Soundness and LART. Most samples which failed Absorption passed Specific Gravity and LART. The correlation between Absorption and Specific Gravity or between Absorption and LART is not good. Most samples which failed Absorption also failed Soundness.

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Non-Specification Tests

The four test methods discussed in this section are Durability, Wet-Dry, Freeze-Thaw and Rapid Abrasion. The Durability test is a California Division of Highways Standard Specification test for certain classes of aggregate, but the other test methods were experimental and considerable developmental work was required.

Experimentation by the authors with the Wet-Dry, Freeze-Thaw, and Rapid Abrasion tests was directed towards development of quantitative test methods. Although some larger blocks were Freeze-Thaw tested, the use of crushed rock fragments was preferred in these tests because testing of a single rock and applying the test results to a large quantity of rocks implies a thorough knowledge of the material and the source, careful selection of the one rock to be tested, and experienced judgment in interpreting and applying the test results. These conditions are not normally met in highway sampling and testing.

The method of performing the tests, the results of the experimental testing, and an evaluation of the test methods are included in the following discussion.

Durability

The method of performing this test (Test Method No. Calif. 229-C) is described in Vol. 1 of the Materials Manual. The durability factor (D_c) for coarse aggregate is described in the Materials Manual as "a value indicating the relative resistance of an aggregate to producing claylike fines when subjected to the prescribed mechanical methods of degradation." The values of D_c range from 0 to 100 with low values obtained for poor material and high values for good. Durability tests were first made on rock slope protection material in October, 1964, and since that time have been performed on all samples containing sufficient material.

A histogram showing the distribution of Durability test results is included in Appendix G. A marked statistical break occurs at a Durability of 65 but this value could not be correlated to performance or results of other tests. Comparison of the field performance of the material and the Durability test results indicate that a D_c of 60 may be a reasonable minimum specification for the Durability test. The data available for analysis is limited, however, and much more data will be required before a D_c specification can be recommended.

As compared to the long period of time and more elaborate equipment required by the Soundness test method, Durability tests can be made rapidly in the District laboratories. An analysis was made to determine if the Soundness test could be eliminated for rocks having D_c test results greater than some particular

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value on the D_c scale (0-100). The analysis showed that 97.4 percent of the samples that had a D_c value of 75 or greater, passed the Soundness test. It is tentatively concluded that the Soundness test need not be performed on samples with D_c values of 75 or greater.

Wet-Dry Test

The following test procedure was used in the initial evaluation of this test method:

1. Oven dried 2500± gram samples of 2½ x 2 inch crushed rock fragments were obtained.

2. The samples were alternately submerged in water for 24 hours and oven dried in a 230°F oven for 24 hours. This constitutes one cycle. This series of tests was concluded after 15 cycles.

3. After the 15th cycle, the material was shaken for 2 minutes on a mechanical sieve shaker using a 3/8 inch sieve.

4. $$\text{Percent loss} = \frac{\text{weight of material lost}}{\text{original weight of sample}} \times 100$$

The normal cycle was interrupted by weekends, and the samples were either soaking or drying for 72 hours. This periodic variation probably had little effect on the results. The short shaking was used to remove any material which may have been loosened during testing.

Figure 4 shows typical samples in the baskets that were used for containers, and the baskets in the soaking tank. The water was kept at a relatively constant room temperature and at a constant depth.

The first series of tests were conducted to determine the relative severity of sea water and tap water. The results of these tests are included in Appendix H. The losses were surprisingly low but did show the tap water test to be the most severe. On the basis of these tests the Wet-Dry test using sea water was discontinued.

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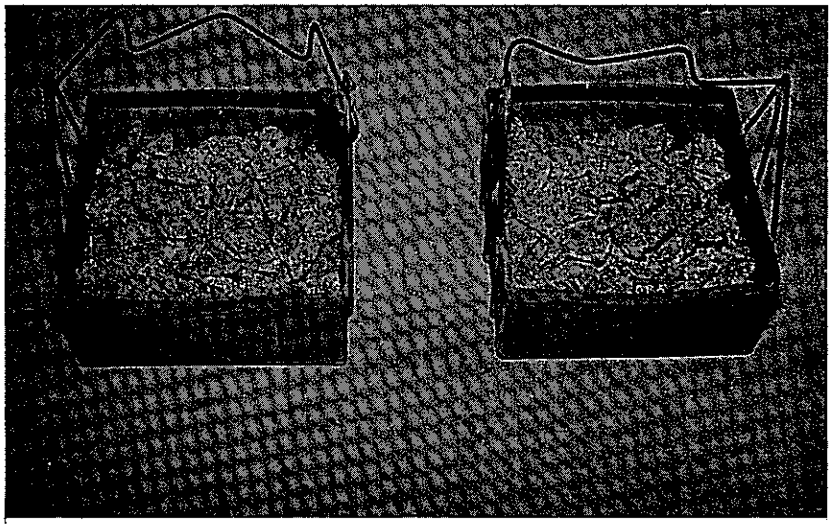
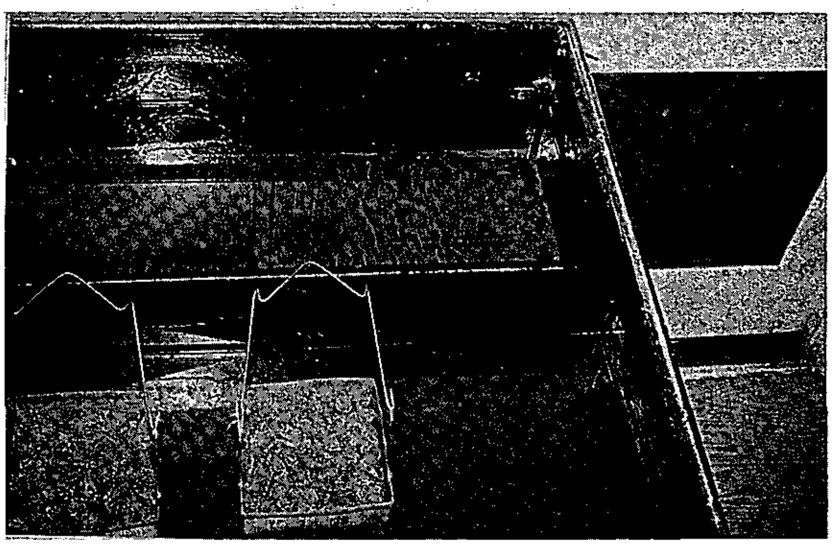


A. Samples in sample baskets



B. Samples in soaking tanks

Figure 4.-Wet-dry test

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An investigation was conducted to determine if salts deposited during the drying portion of the cycle might explain the differences in weight loss between fresh water and sea water samples. Rock from the sea water test was boiled in distilled water and the solution was tested with a silver nitrate solution. An abundant chloride precipitate was obtained. No quantitative measurement of the salt residue was made due to the difficulty of the procedure and the length of time required. Since the differences in weight loss between samples soaked in sea water and samples soaked in tap water are small, deposited salts appear to be a reasonable explanation.

The second series of tests, using only tap water, was performed to determine the correlation between Wet-Dry test results and both field performance and Specification test results. Several rock types from different environments were represented in the samples used for this series of tests.

Results of this series of tests are included in Appendix H. Analysis of this data indicated that no direct relationship exists between Wet-Dry test results and either performance or Specification test results. The losses were again very small.

The third test series investigated the effect of shorter soaking and drying times, increasing the number of cycles, using wetting agents, and using different temperatures for drying. The previous test procedure was used but 1½ x 1 inch crushed rock fragments were substituted for the 2½ x 2 inch size. A study of these factors was considered essential in attempting to increase the severity of the Wet-Dry test.

Increasing the number of cycles, shortening the soaking and drying times, using different drying temperatures, and using a wetting agent did not significantly increase the severity of the test method. Decreasing the particle size did increase the severity of the test because of the increased surface area on which the water could act.

The fourth series was performed using the following test procedure:

1. Oven dried 2500± gram samples of crushed rock fragments of different sizes were obtained. (Table 13).

2. The samples were alternately submerged in water for 8 hours and oven dried in a 230°F oven for 16 hours. This constituted one cycle and this series of tests was concluded after 15 cycles.

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3. After the 15th cycle, the material is shaken for two minutes on a mechanical sieve shaker using a half size sieve, e.g., for $1\frac{1}{2}$ x 1 inch aggregate a $\frac{1}{2}$ inch sieve was used and for 3/8 inch x No. 4 aggregate a No. 8 sieve was used.

4. Percent loss = $\frac{\text{weight of material lost}}{\text{original weight of sample}} \times 100$

Again the cycles were interrupted by weekends but the effect of this is believed to be small. The results of this test series are included in Appendix H and show that using smaller particle sizes will increase the severity of the test but not to any useful extent.

In summary, our investigation of a Wet-Dry test indicates that it lacks severity, small fragments have more loss than larger fragments, tap water is more severe than sea water, wetting agents will not appreciably increase the severity of the test, and increasing soaking and drying time or increasing the number or cycles does not necessarily increase the loss. The relatively long time (3 weeks) required to perform this test, the poor quantitative results, and the lack of correlation to performance or other test methods indicates that this test method is unsatisfactory for quality control purposes. It is believed the variance of this conclusion from that reached by Drew and Woods (1960, p.379) is due primarily to the greater variety of rock types that were tested during the present investigation.

Freeze-Thaw Test

A study was made to determine the effect of repeated freezing and thawing on samples of rock slope protection material.

A Conrad freeze-thaw chamber (Fig. 5) was used in this study. The machine is automatic and was set to complete a freeze-thaw cycle every four hours. During this period of time the temperature in the test chamber is lowered to approximately -16°F, and then raised to approximately 65°F. by circulating tap water. The temperature is measured at the center of a six-inch diameter concrete cylinder which is placed in the chamber with the samples. The machine is provided with a continuous chart recorder which shows the temperature at any given time. Figure 6 shows a typical chart from the recorder. Notes on this chart indicate the time and sequence of events which occur during one cycle. The samples are below 32°F for approximately $2\frac{1}{2}$ hours and they are submerged in the thaw water for approximately $1\frac{1}{2}$ hours. The conditions in the test are probably similar to those encountered on an installation in a natural freeze-thaw environment.

All of the tests were arbitrarily terminated at the end of 200 cycles. The time required for this number of cycles

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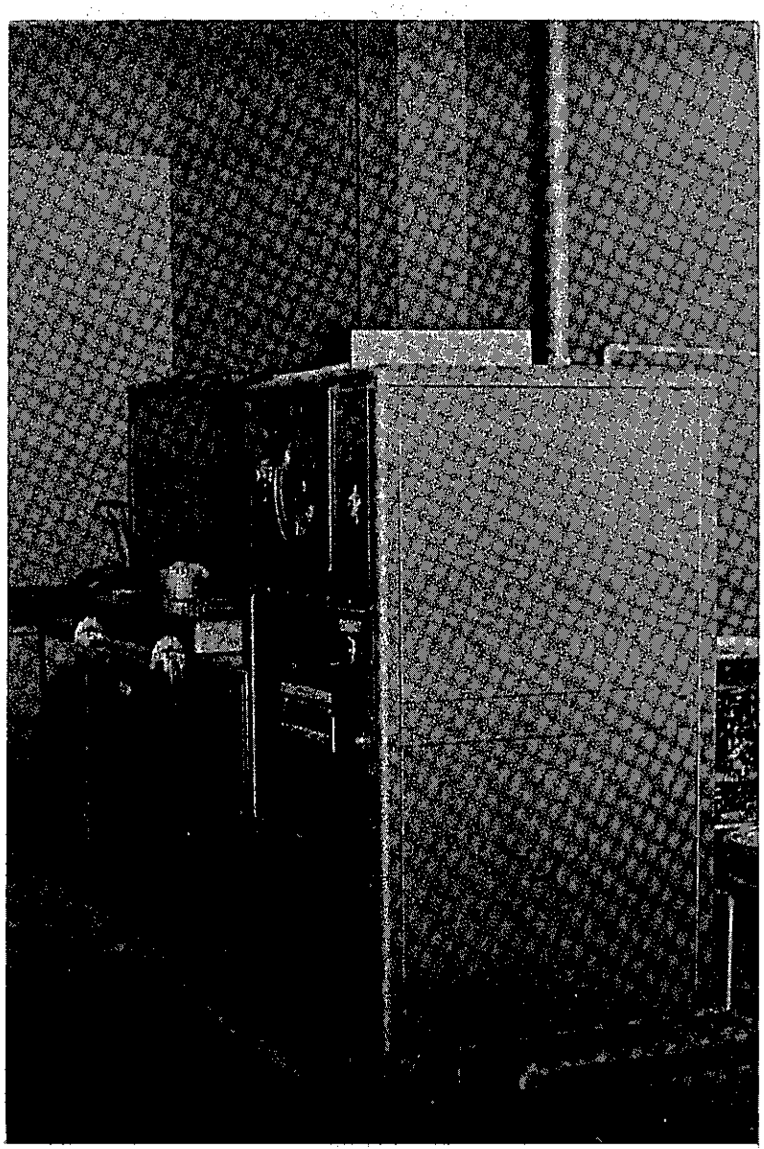

Figure 5.-Conrad freeze-thaw chamber

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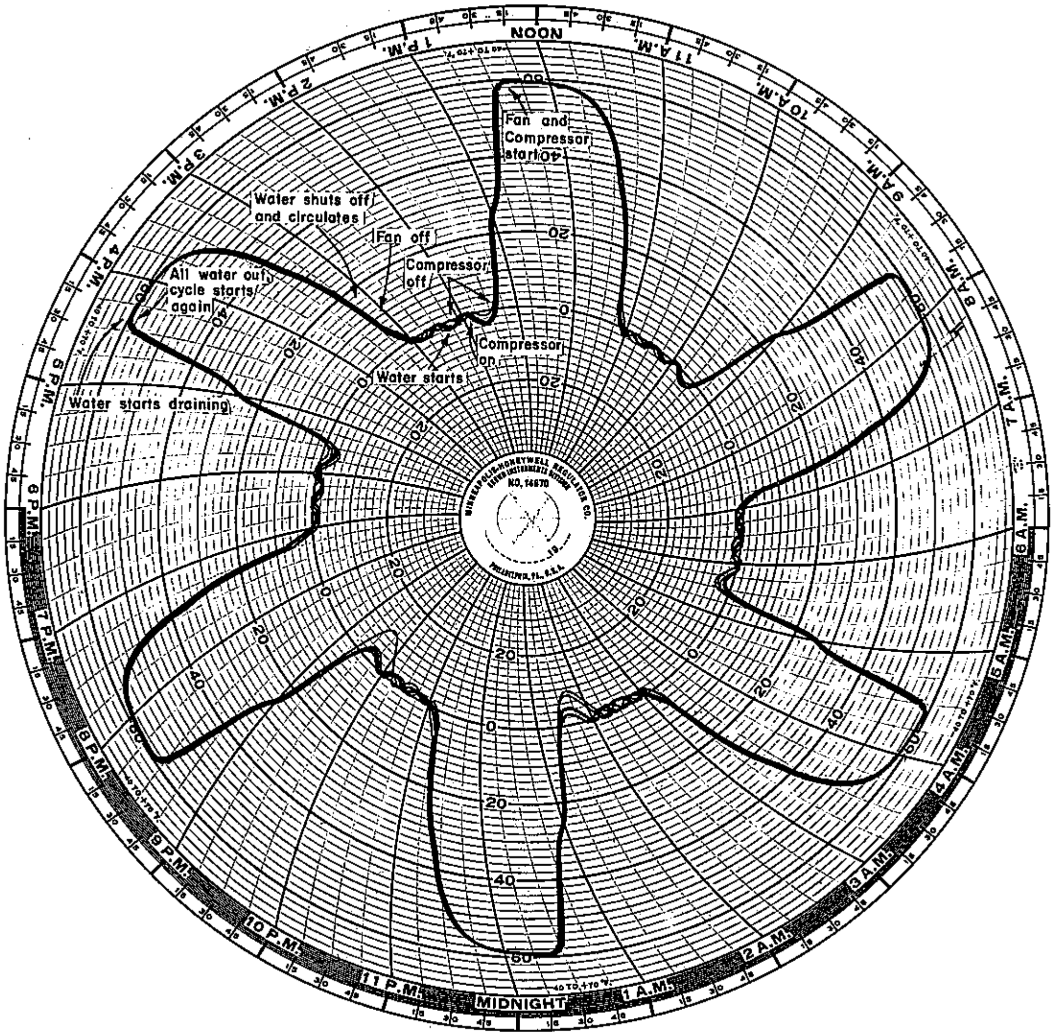

Figure 6.-Freeze-thaw chart

(33.3 days) is beyond the limit of a practical quality control test. Any serious defects in the samples should become apparent during this period of time.

The initial attempt to evaluate this type of test consisted of placing hand-sized samples of rock into the freeze-thaw chamber. Dry weights were obtained before and after the test by drying the samples in a 230°F oven for 64 hours.

The samples were all obtained from installations on which the performance of the material had been evaluated. Many types of rock are represented in this study and many of the samples did not comply with present specifications. Two samples were tested in both an intermittent and a continuous immersed condition.

Results of these tests are included in Appendix I. Analysis of these results indicate a lack of correlation with known performance. Only four samples out of 35 had losses greater than 2 percent and only seven had losses greater than 1 percent. The two continuously immersed samples had losses greater than 1 percent and also had losses greater than the intermittently immersed samples of the same material. Only 2 samples of granular rocks, both of which had poor performance histories and failed the specification tests, disintegrated. The remaining samples with significant losses all failed on fractures or veins.

Samples in the frozen condition are shown in Figure 7-A. The appearance of these samples at the completion of 200 cycles is shown in Figure 7-B. A sandstone and a corase grained granitic rock showed extensive disintegration. A foliated granite (Figure 8-A) and a fractured andesite (Figure 8-B) broke along pre-existing fractures. An ultrabasic rock (Figure 9) was fragmented along seams of expansive secondary minerals. Sound unfractured rock such as vesicular olivine basalt (Figure 10) was not visibly affected by this test.

An attempt to determine the relative severity of intermittent submersion and continuous submersion was made. 2500-gram samples of 1 x 3/4 inch crushed rock fragments were used. No significant differences were found between alternate wetting and drying and continuous submersion with these samples.

The Freeze-Thaw test appears to be most effective in attacking rocks with zones of structural weakness such as foliation, fractures, veins, and seams. These features are destroyed in the process of crushing and screening and, therefore, crushed rock should perform well in this test whether submerged or not. This was true in the above described series of tests for evaluating the relative severity of intermittent submersion and continuous submersion.

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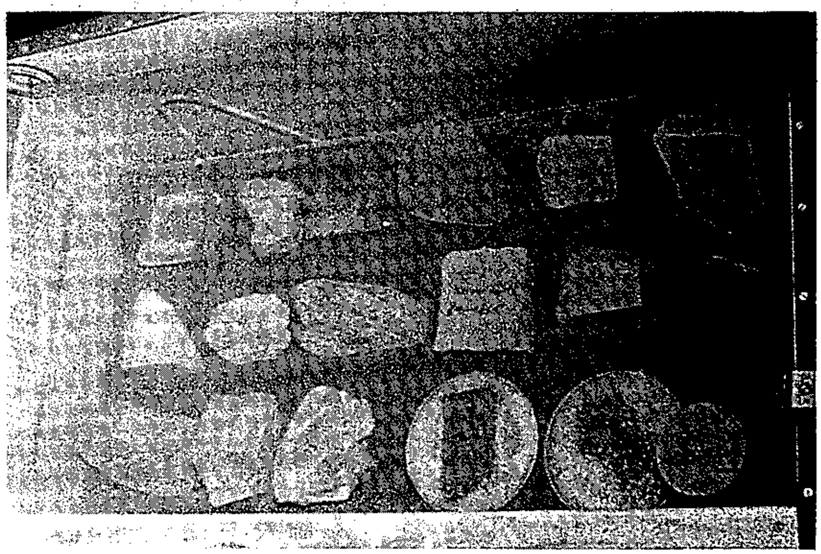
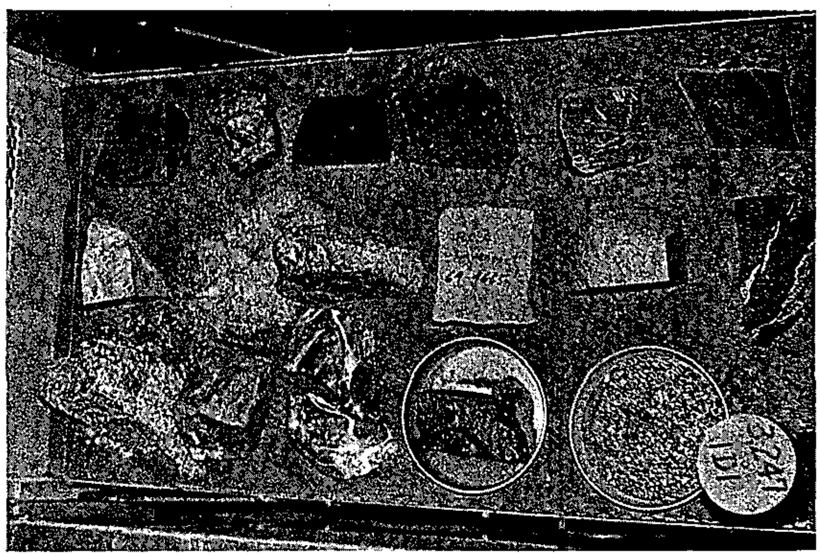


A. In frozen condition



B. After 200 cycles

Figure 7.-Samples in freeze-thaw chamber

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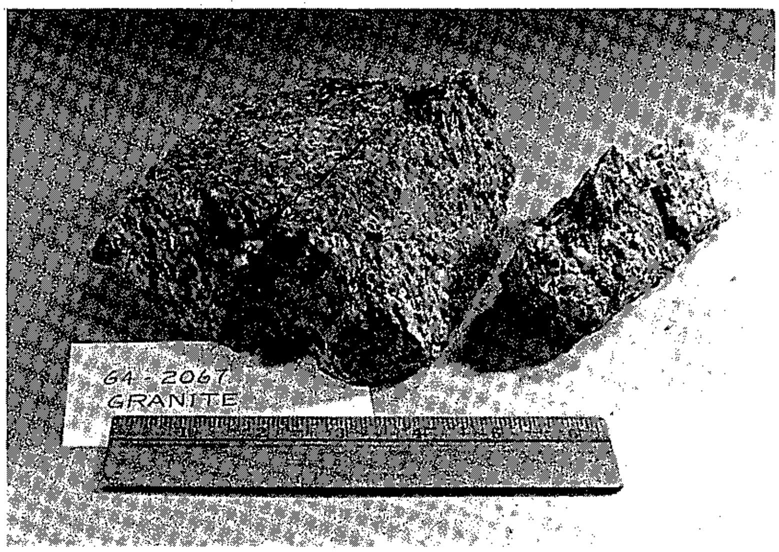
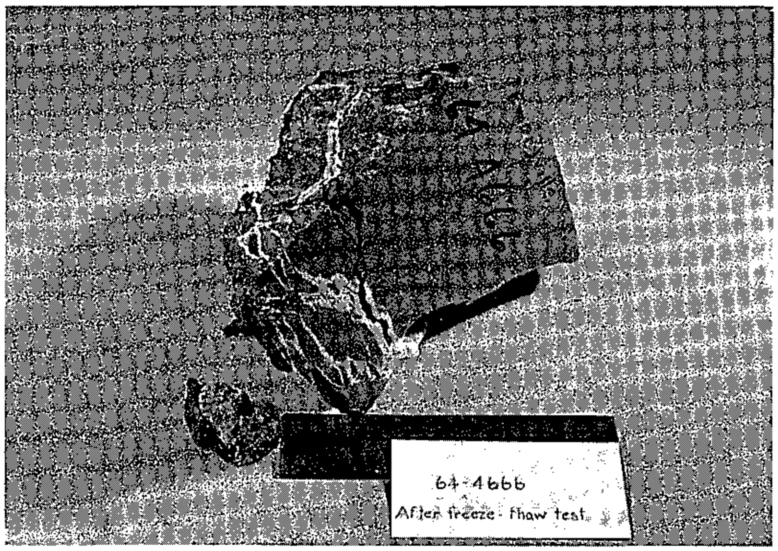


A. Granite (foliated)



B. Andesite

Figure 8.-Freeze-thaw samples with fractures

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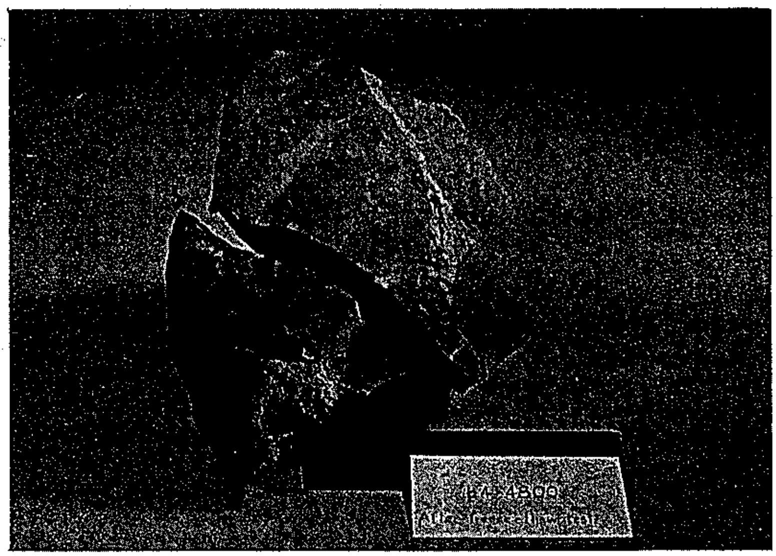

Figure 9.-Freeze-thaw sample with expansive minerals

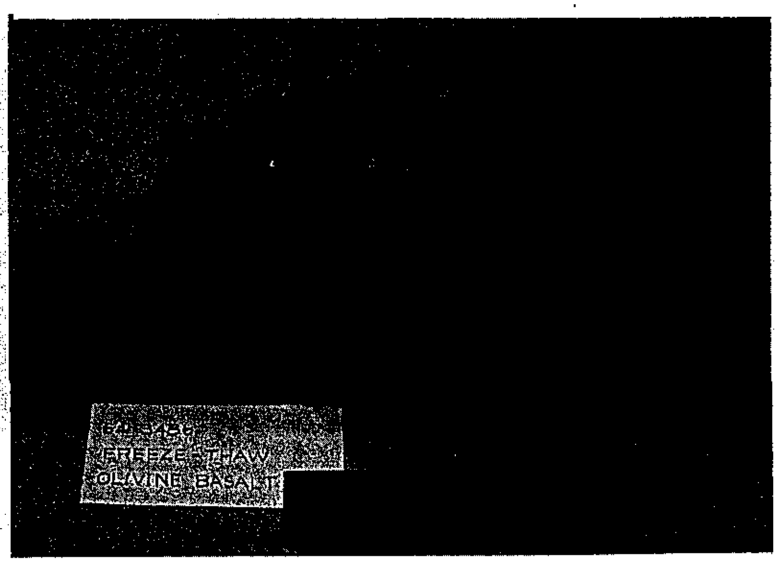

Figure 10.-Freeze-thaw sample of sound unfractured rock

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An additional series of tests was performed with crushed rock to determine if the size of crushed particles had any effect on the percent loss. Results indicate that for a given material the loss will be greater for fine fragments than for coarse.

In summary, the Freeze-Thaw test is not satisfactory for a specification test because of the time required to perform the test and because the percent loss is too small for comparative purposes. The test does have value in evaluating the degree to which such features as foliation, fractures and veins affect the performance of a material.

The Concrete Section of this department, in an unpublished report, was unable to determine any correlation between the Freeze-Thaw and Soundness test. Our study indicates that the Freeze-Thaw test does not correlate with any of the specification tests.

Rapid Abrasion Test

Resistance to abrasion is a desirable property for rock slope protection material. The Los Angeles Ratter test has been employed as a measure of this property, but this test primarily measures impact resistance. In an effort to measure resistance to abrasion as an independent property, the testing program described below was undertaken.

Abrasion of rock slope protection material is normally caused by water-borne particles. The techniques used in the tumbler-type rock polishers approach this condition, and development of a suitable test method using these techniques was undertaken.

A steel paint mill with an inside diameter of 5-1/8 inches and an inside height of 6 inches was used as a tumbler. The samples were tumbled on a paint roller for 8 hours at 66 rpm. A close-up of the paint mill is shown in Figure 11-A and the paint mill on the paint roller in Figure 11-B. Ordinary tap water was used in all tests and the oven dry weights were obtained by drying the samples in a 230°F oven for 16 hours. The percent loss was calculated using the following formula:

$$\text{percent loss} = \frac{\text{weight loss}}{\text{original weight}} \times 100$$

Although a detailed test method has not been developed, considerable experimentation with a method has been completed. These experiments were done using the paint roller and paint mill described above, and olivine basalt for test samples.

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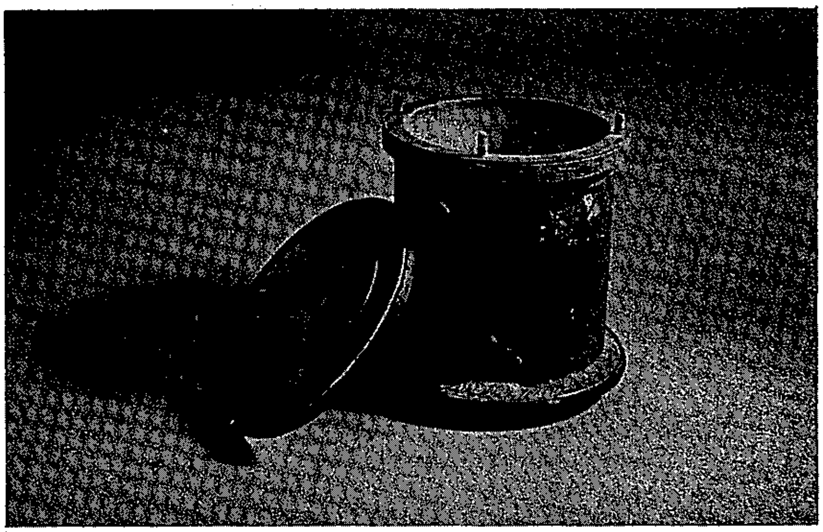
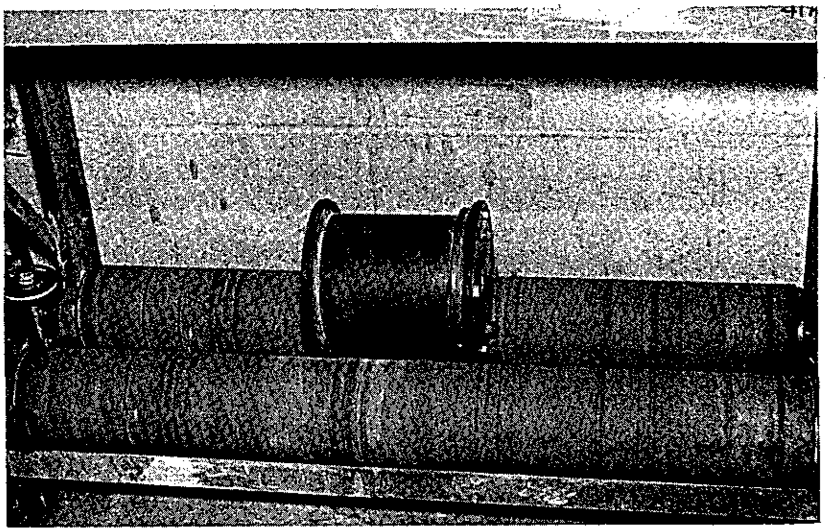


A. Paint mill



B. Paint mill on roller

Figure 11.-Rapid abrasion test equipment

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The studies indicate that 1000 grams of 3/4 x ½ inch crushed rock particles, 35 grams of closely graded #30 silicon carbide abrasives and enough water to cover the sample and abrasive in the paint mill will provide the optimum loss. The inter-relationship of these factors and the effect of different types of material was not studied. Such a study should be made before establishing a definite test method.

The early test results were not reproducible. This condition was caused by a combination of such diverse factors as variable material, variable sample weight, and variable particle size and shape. To reduce the effect of these factors, the test procedure was revised to use a relatively small particle size and a fixed sample weight, and the loss was calculated as an average loss of 3 samples. Tests, using this revised procedure, indicate that results can be reproduced to plus or minus 0.1 percent loss.

The test procedure described below was used on nearly all samples obtained as part of our investigation of the field performance of rock slope protection material. This testing was performed to determine the effectivenss of this type of test in predicting the field performance. Since this testing was performed concurrently with the experimental testing the procedure was somewhat different than for optimum conditions. This procedure was continued in order to obtain comparative results.

1. Place 1500± ½ grams of 1 x 3/4 inch crushed rock fragments in the steel paint mill and add 150 grams of #30 silicon carbide abrasive grit. Add enough tap water to cover the sample and abrasive.

2. Roll on a 66 rpm paint roller for 8± ¼ hours.

3. Remove all fragments of rock larger than #4, wash thoroughly and oven dry for 16 hours at 230°F.

4. Percent Loss = $\frac{\text{weight loss}}{\text{Original weight}} \times 100$

5. An average of 3 test results for a given material is the Rapid Abrasion loss for that material.

Results of all these tests are included in Appendix J.

The "before" and "after" appearance of samples of two types of rock used in this study are shown in Figure 12 and Figure 13. This appearance is typical of all samples tested and shows very clearly the extreme rounding and smoothing which occurs in this test.

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Figure 12.-Rapid abrasion sample

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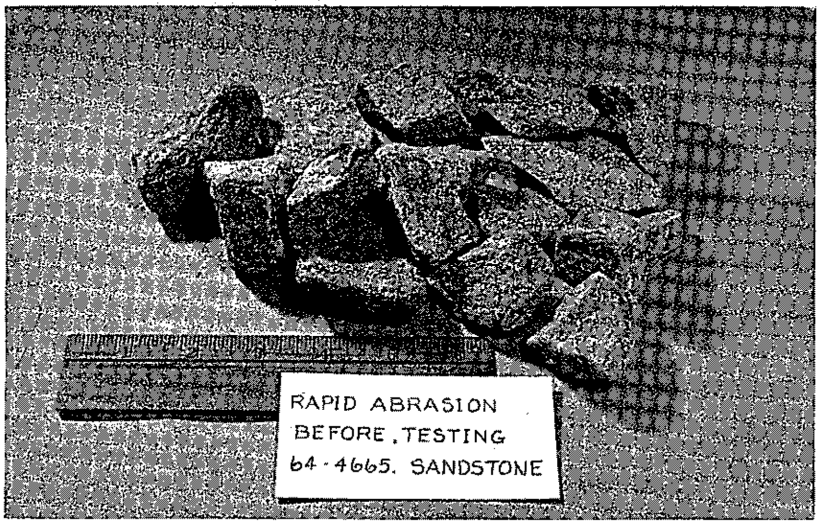

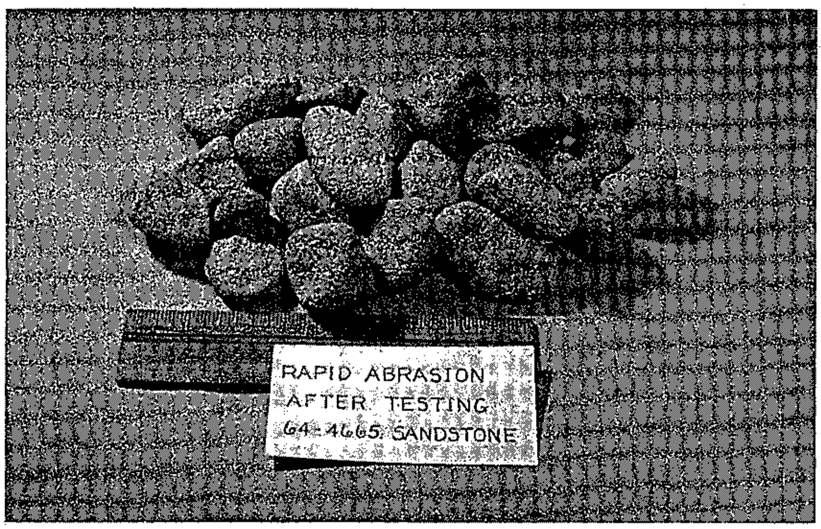

Figure 13.-Rapid abrasion sample

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This test shows promise as a specification test because of the ease and speed of the procedure and because of an apparently useful correlation of the results with the actual field performance (page 16). Before adoption of this test as a specification test however, considerable testing should be completed. The relationship between the test procedure and the type of rock has not been investigated at all and is of the utmost importance.

Petrologic Methods

Petrography, X-ray diffraction, Differential Thermal Analysis: These three methods of classification and mineral identification are available at the Materials and Research Laboratory. Petrography is the only method regularly used for evaluating rock slope protection at the laboratory. However, there are no specifications for this method and none are proposed in this report. The X-ray diffraction and D.T.A. methods are used when more information is desired for a sample of special interest.

All rock slope protection material submitted to the laboratory for testing is examined and classified by use of a binocular microscope. Thin section studies or examination of powders in immersion media are generally used only in research studies or in studies of materials with special problems. The time required to make and analyze thin sections reduces the desirability of this method for routine samples. A petrographic examination of powdered rock permits the identification of minerals that cannot be readily identified with the binocular microscope, but the rock texture and structure must still be studied in thin section or with the binocular microscope.

Thin sections were made of many samples of riprap that were taken during the course of this study. A number of X-ray diffraction and D.T.A. analyses were made by using portions of the chips from which the thin sections were made. These three methods used in conjunction will normally give the mineral composition including the clay minerals, secondary minerals and alteration of primary minerals, approximate percentages for some minerals, textural details, and rock classification.

The combined results from these three methods yield information that: (1) can be used for predicting the performance of rock slope protection material; and (2) cannot be obtained or inferred from the specification test results.

It is recommended that greater use be made of these methods to better determine the probable performance of rock slope protection material. To obtain good results from these specialized techniques they must be performed by qualified personnel experienced in their use.

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

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APPENDIX A

Brass Tags

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Brass Tags

An experimental technique for measuring the amount and rate of decrease in the size of rocks on an installation is being tested on several rock types and in several environments. The method consists of attaching a 1-3/8 inch diameter brass disc to a convenient spot on the rock to be measured. These brass tags are numbered and have a cross inscribed on the upper surface.

The lower surface of the brass tags are sandblasted and cleaned with acetone to provide a more positive bond. The brass tags are attached to the rock by means of a quick setting two-component epoxy adhesive. To determine the effectiveness of the adhesive, a rock with a tag attached was soaked in ocean water for 21 days, and was tested for 15 cycles in the wetting and drying test with temperatures up to 230°F, and for 200 cycles in the freeze-thaw chamber with temperatures down to -6°F. No deterioration of the adhesive bond occurred.

A standard 6-inch depth gauge graduated in hundredths of an inch is placed on the disc and measurements to the surface of the rock are made. The measurements are made at a fixed and constant distance from the brass disc and in the two most convenient directions indicated by the inscribed cross.

It is believed that periodic readings may provide data on the rate at which material is being removed from the surface of the rock thereby decreasing its size and weight.

Thirty-five tags have been installed on sandstone, granitic and volcanic rocks, schist and limestone, and in both salt and fresh water environments, but sufficient time has not elapsed to permit an evaluation of the validity of this technique.

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APPENDIX B

Installations and Quarries

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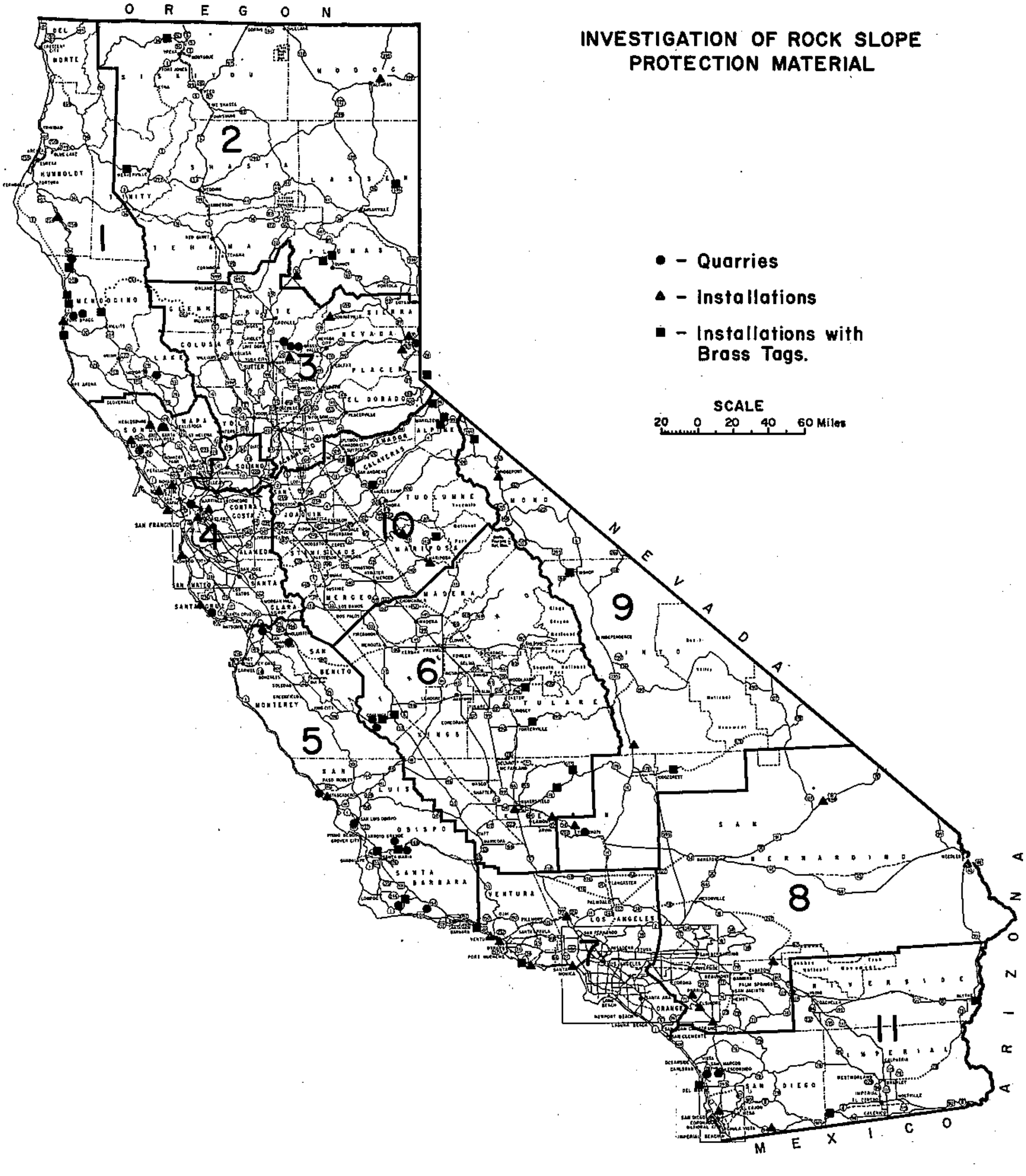

Figure 14. Location of Installations and Quarries

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Table 7.-Summary of Installations

Dist	Co	Rte	Location	Source	Rock Type	Year: Install	Year: Inspect	Spec Test Results: SpGr	Abs	LART	Sound	Rock* Quality
01	Men	1	Big River Bridge	Pudding Creek	Sandstone	1961	1965	2.67	2.1	47	48.1	U
01	Men	-	Noyo Break-water	Pudding Creek, Davenport	Sandstone	1931, 1954	1966	-	-	-	-	-
01	Men	1	DeHaven Creek Bridge	Cottoneva Creek	Sandstone	1964	1965	2.68	1.7	40	4.9	G
01	Men	1	Juan Creek Bridge	Cottoneva Creek	Sandstone	1960	1965	2.67	1.7	36	8.5	G
01	Hum	101	Weott	Salmon Creek	Sandstone	1964	1965	2.54	2.0	28	1.9	V
01	Men	101	Red Mountain Creek	Red Mountain Creek	Sandstone	1954	1965	2.67	2.5	43	9.4	M
01	Men	101	Longvale	Local	Glaucophane schist	1957	1965	3.16	0.4	16	0.4	V
02	Tri	299	Helena	Local	Schistose metagabbro	1940	1966	2.97	0.4	17	3.2	V
02	Sis	96	Klamath River	Local	Ultrabasic	1965	1966	3.03	0.3	24	0.4	V
02	Mod	395	Alturas	Local	Basalt	1955	1966	2.76	2.0	32	1.7	V
02	Las	395	Secret Valley Creek	Local	Basalt	1954	1966	2.84	1.5	22	0.7	V
02	Plu	89	Indian Creek	Local	Granite	1957	1966	-	-	-	-	-
02	Plu	70	Feather River	Local	Granite	1957	1966	-	-	-	-	-
02	Plu	70	Elephant Butte	Local	Granite	1957	1966	-	-	-	-	-
03	Yub	20	Parks Bar Bridge	Parks Bar Bridge	Andesite	1963	1964	2.99	0.7	12	0.5	V
03	Sie	49	N. Yuba River Bridge	Local	Schist	1964	1964	2.96	0.9	20	1.6	G
03	Nev	Old 40	Flycasters Bend	Local	Olivine basalt	1951	1964	2.72 2.60	1.9 3.2	39 37	1.7 1.5	G G
03			Cave Rock, Nevada	Local	Dacite	1957	1964	2.67	3.4	54	33.3	U
03	Pla	89	Squaw Creek	Local	Tuff	1959	1964	2.80	1.9	32	3.7	M
04	Son	1	Healdsburg	Brooks	Olivine basalt	1954	1964	2.72	1.8	13	1.0	V

* U - unsatisfactory G - good
M - marginal V - very good

Table 7.-Summary of Installations-Continued

Dist	Co	Rte	Location	Source	Rock Type	Year Install	Year Inspect	Spec Test Results SpGr	Abs	LART	Sound	Rock* Quality
04	Son	12	Duncans Mills	Local	Sandstone	1960	1964	2.63	9.7	52	54.7	U
04	Mrn	FAS 1278	Lake Nicasio	Local	Olivine gabbro	1961	1964	3.01	1.2	22	2.4	G
04	Mrn	FAS 608	Tocaloma	San Rafael	Sandstone	1963	1964	2.72	1.3	19	2.7	G
04	Mrn	1	Bolinas Bay	Leonards	Sandstone	1962	1964	2.68	1.4	17	1.6	V
04	CC	-	Briones Dam	Quarry Products	Sandstone	1964	1964	2.73	1.3	18	4.9	G
04	Ala	80	Ashby St.	H & C Quarry	Andesite breccia	1952	1964	2.85	6.5	30	45.5	U
04	SM	-	Pillar Point Breakwater	Davenport -	Sandstone	1961	1964	2.66	2.0	45	17.7	G
04	SCr	1	Waddell Bluffs	Big Creek	Quartz diorite	1948	1964	2.74	0.9	33	8.7	G
05	SLO	1	Ricioli Ranch	Ricioli	Glaucophane schist	1961	1965	3.12	0.5	36	1.4	G
05	SLO	101	Nipomo Creek	Johnson	Sandstone	1958	1965	2.76	2.2	25	25.0	U
05	SB	101	Santa Ynez River	Crawford	Limestone	1964	1965	2.66	0.7	34	2.1	V
05	SLO	166	Cuyama River	Chimney, Aliso Canyon	Sandstone	1959	1965	2.68 2.74	1.6 0.5	25 15	1.9 0.8	G
06	Fre	198	Wartham Creek	Wartham Creek	Sandstone	1942	1965	2.65	1.3	55	38.1	M
06	Fre	33	Jacalitos Creek	Wartham Creek	Sandstone	1963	1965	2.65	1.3	55	38.1	M
06	Ker	155	French Gulch	Local	Granodiorite	1953	1965	2.71	0.4	52	1.5	V
06	Ker	58	Caliente Creek	Local	Metagranitic rock	1960	1965	2.89	0.6	40	1.1	V
06	Ker	178	Kern River	Local	Quartz diorite	1951	1965	2.74	0.4	41	0.5	V
06	Tul	198	Horse Creek	Local	Granodiorite	1961	1965	2.79	0.5	43	0.8	V
06	Tul	190	Success Reservoir	Local	Mixed granitic rocks	1958	1965	-	-	-	-	-
06	Ker	99	Kern River Bridge	Kern River	Mixed granitic & metamorphic boulders	1961	1965	-	-	-	-	-
07	Ven	101	Rincon Point	Rincon	Sandstone	1955	1966	-	-	-	-	-
07	Ven	-	Ventura Beach State Park	Conejo	Andesite	1961	1966	2.57	5.3	28	3.8	G

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Table 7.-Summary of Installations-Continued

Dist	Co	Rte	Location	Source	Rock Type	Year		Spec Test Results				Rock* Quality
						Install	Inspect	SpGr	Abs	LART	Sound	
07	Ven	-	Ventura Marina	Hawley	Agglomerate	1960	1966	2.52	6.0	23	13.9	M
07	Ven	1	La Jolla Canyon	Riverside	Granite	1950	1966	2.79	0.3	43.2	1.0	V
07	Ven	1	Big Sycamore Canyon	Big Sycamore	Sandstone	1953	1966	2.66	1.0	42	11.3	G
07	LA	-	Will Rogers State Park	Topanga Canyon	Conglomerate	1960	1966	-	-	-	-	-
07	LA	5	Santa Clara River	-	Anorthosite	1964	1966	2.71	0.7	44	2.8	V
08	Riv	62	Morongo Valley	Local	Biotite gneiss	1963	1966	2.74	0.9	47	8.5	M
08	Riv	71	Alberhill	Local	Dacite porphyry	1958	1966	2.68	1.0	25	9.4	G
08	Riv	71	San Jacinto River	-	Quartz diorite	1956	1966	-	-	-	-	-
08	Riv	395	Temecula	Local	Quartz diorite	1952	1966	2.66	0.6	53	3.3	G
08	SBd	40	Topack	Local	Metadiorite	1957	1966	2.82	0.8	20	5.7	G
08	SBd	15	Halloran	Local	Basalt	1961	1966	2.84	1.3	15	0.8	V
09	Mno	395	Walker River	Local	Granite	1951	1966	2.63	1.3	74	14.4	G
09	Mno	395	Virginia Creek	Local	Dacite porphyry	1959	1966	2.65	5.4	35	32.8	M
09	Iny	168	Bishop	Local	Granite	1965	1966	2.72	0.7	55	3.3	G
09	Iny	395	Little Lake	Local	Gneissic granite	1962	1966	2.75	0.9	38	3.4	G
09	SBd	178	Salt Wells Canyon	China Lake	Granodiorite	1964	1966	2.74	0.4	29	0.8	V
09	Ker	58	Tehachapi	Local	Quartz diorite	1964	1966	2.76	0.4	21	0.7	V
10	Alp	89	West Carson River	Local	Granite	1965	1965	2.62	0.2	60	2.2	G
10	Alp	89	Hangmans Bridge	Local	Agglomerate	1964	1965	2.58	4.1	33	26.7	U
10	Alp	4	East Carson River	Local	Silicified tuff	1957	1965	2.49	1.4	15	0.7	G
10	Cal	4	Angels Camp	Local	Schist	1962	1965	2.94	0.4	17	0.8	V
10	Mpa	132	Coulterville	Local	Mariposite	1964	1965	2.92	0.4	22	1.8	V
10	Mpa	49	Mariposa	Local	Basic hornfels	1964	1965	3.14	0.9	20	0.5	V
10	Mpa	140	Merced River	Local	Phyllonite	1957	1965	2.71	0.5	21	1.6	G

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Table 7.-Summary of Installations-Continued

Dist	Co	Rte	Location	Source	Rock Type	Year		Spec Test Results				Rock* Quality
						Install	Inspect	SpGr	Abs	LART	Sound	
10	Ama	49	Butte City	Local	Diorite	1964	1965	2.92	0.4	19	1.6	V
11	SD	5	Cardiff	Meadowlark, Harmony	Granite, Gabbro	1961 1959	1966	2.68 2.94	0.6 0.2	23 16.8	0.9 -	V
11	SD	8	Sandrock Road	V. R. Dennis	Meta-andesite	1959	1966	2.82	0.4	13	0.7	V
11	SD	94	Cottonwood Creek	Local	Quartz diorite	1954	1966	2.63	0.8	57	2.7	G
11	Imp	8	Devils Canyon	Local	Quartz diorite	1963	1966	2.74	0.5	40	2.8	G
11	Riv	10	Colorado River	Cox	Granite	1960	1966	-	-	-	-	-

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Table 8.-SUMMARY OF QUARRIES

Dist	Co	Rte	Location	Rock Type	Year Inspect	Spec Test Results				Rock* Quality
						SpGr	Abs	LART	Sound	
01	Men	-	Pudding Creek	Sandstone	1966	2.66	2.2	54	76.3	U
01	Men	-	Coughborn Ranch	Sandstone	1966	2.69	1.4	22	7.5	M
01	Men	-	Red Mountain Creek	Sandstone	1965	2.65	2.5	43	9.4	M
01	Lak	-	Kelseyville	Porphyritic Andesite	1965	2.55	1.1	67	3.3	G
03	Yub	-	Spring Valley Road	Andesite	1964	2.99	0.4	13	0.4	V
03	Yub	-	Parks Bar	Andesite	1964	2.99	0.7	12	0.5	V
03	Yub	-	Timbuctoo	Meta volcanic	1964	-	-	-	-	-
03	Nev	-	Flycasters	Olivine Basalt	1964	2.72	1.9	39	1.7	V
04	Son	-	Brooks	Olivine Basalt	1964	2.72	1.8	13	1.0	V
04	Son	-	Camp Meeker	Schistose Ultrabasic	1964	3.01	0.9	18	0.8	G
04	CC	-	Quarry Products Inc.	Sandstone	1964	2.73	1.3	18	4.9	G
04	SCr	-	Davenport	Sandstone	1964	2.66	2.0	45	17.7	G
05	Mon	-	Logan	Quartz Diorite	1964	2.86	1.8	39	10.9	G
05	SLO	-	Ricioli Property	Glaucophane Schist	1965	3.12	0.5	36	1.4	G
05	SLO	-	Johnson Property	Sandstone	1965	2.76	2.2	25	25	U
05	SB	-	Bazzi Property	Limestone	1965	2.69	0.6	25	2.8	V
05	SB	-	Crawford	Limestone	1965	2.66	0.7	34	2.1	V
05	SLO	-	Chimney Canyon	Sandstone	1965	2.68	1.6	25	1.9	G
05	SLO	-	Aliso Canyon	Sandstone	1965	2.74	0.5	15	0.8	G

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Table 8.-SUMMARY OF QUARRIES-CONTINUED

Dist	Co	Rte	Location	Rock Type	Year Inspect	Spec Test Results				Rock* Quality
						SpGr	Abs	LART	Sound	
05	SBt	-	Hollister	Dolomite	1965	2.86	0.4	51	1.3	M
06	Fre	-	Wartham Creek	Sandstone	1965	2.65	1.3	55	38.1	M
09	Ker	-	Tehachapi	Limestone	1966	2.72	0.4	43	1.5	G
11	SD	-	Harmony Grove	Gabbro	1966	2.94	0.2	16.8	-	V
11	SD	-	Meadowlark	Granite	1966	2.68	0.6	23	0.9	V

*U - Unsatisfactory G - Good
M - Marginal V - Very Good

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APPENDIX C

Sodium Sulfate Soundness Test

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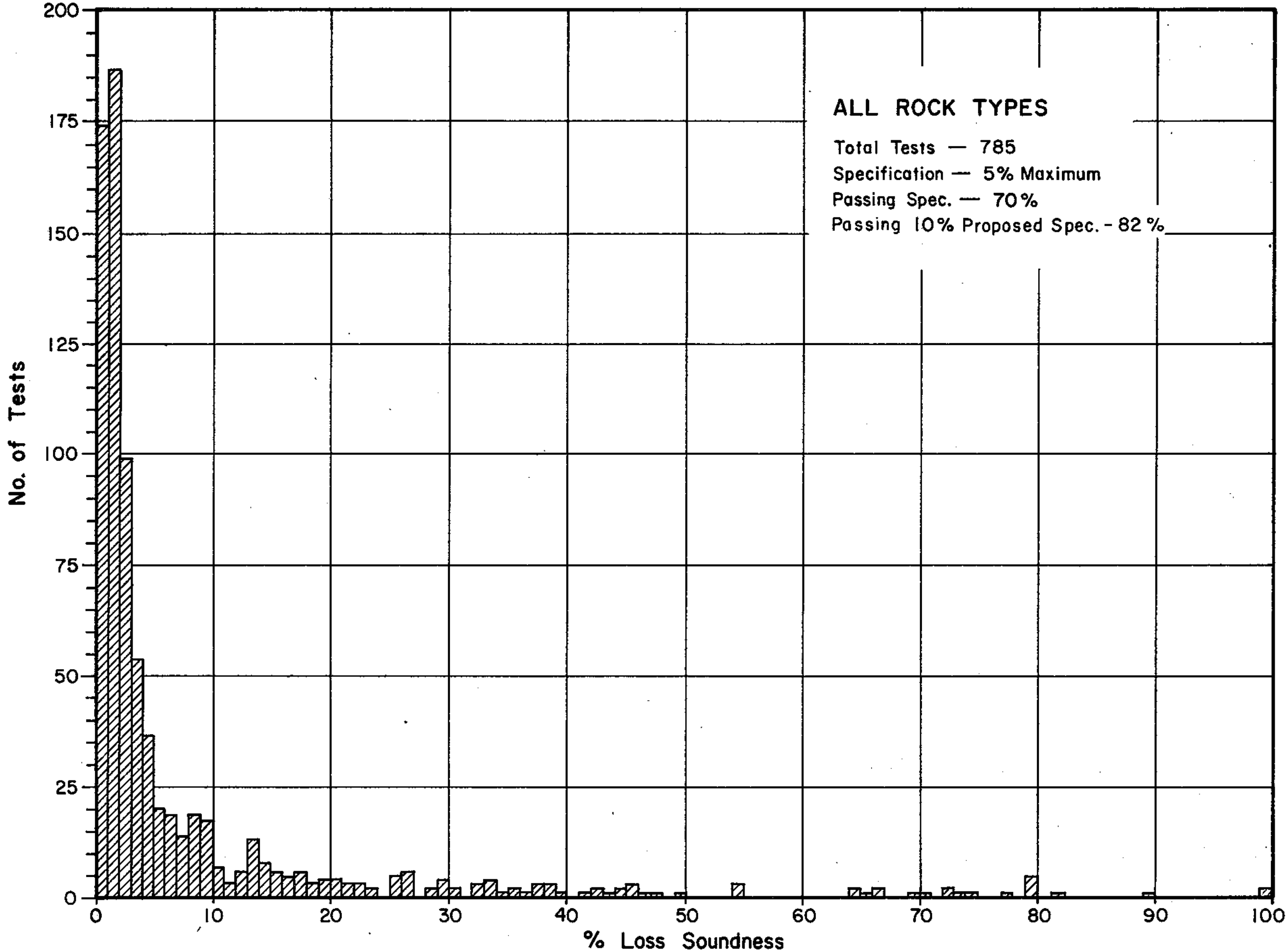

Figure 15.-Distribution of Soundness test results

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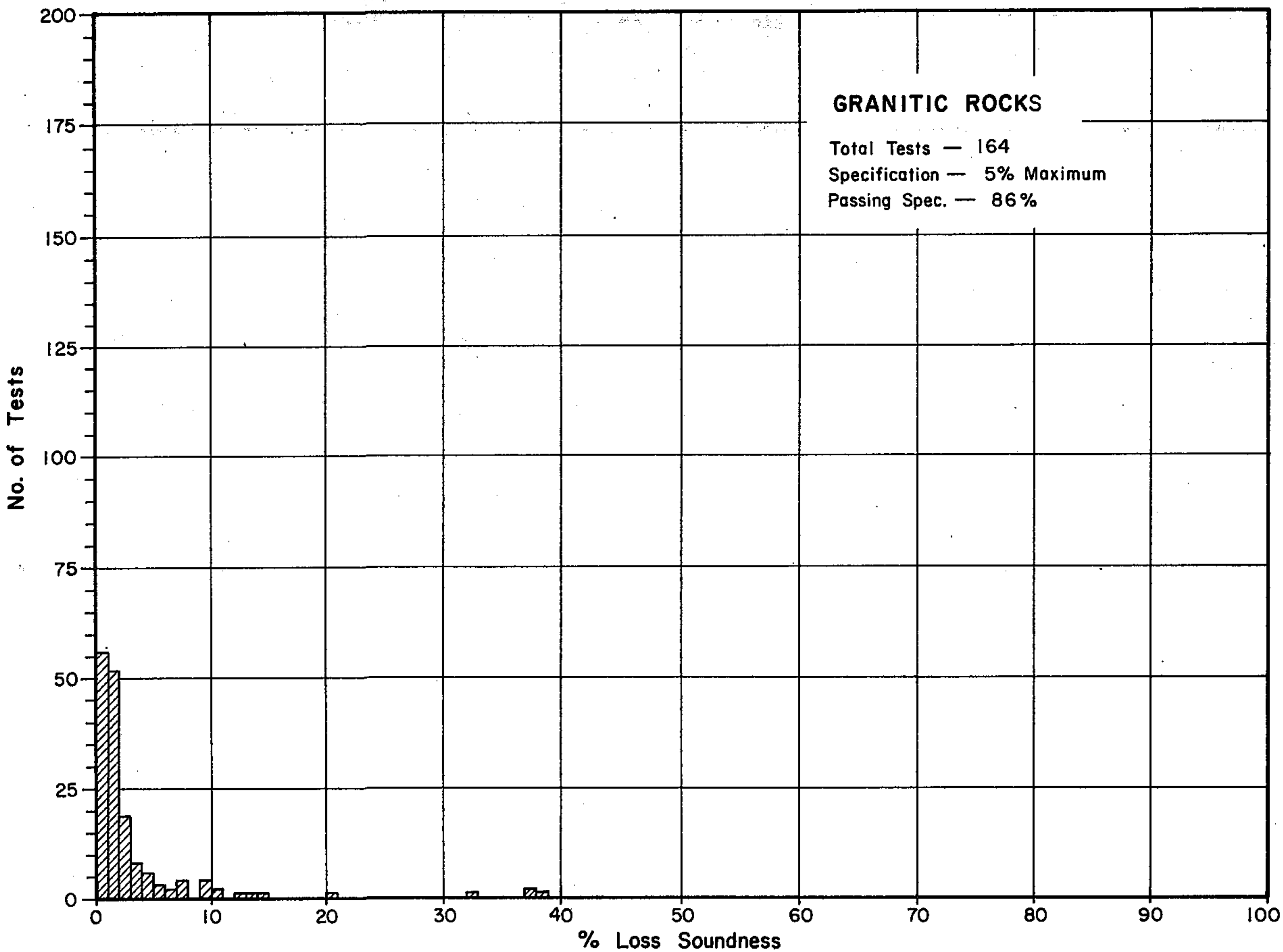

Figure 16.-Distribution of Soundness test results

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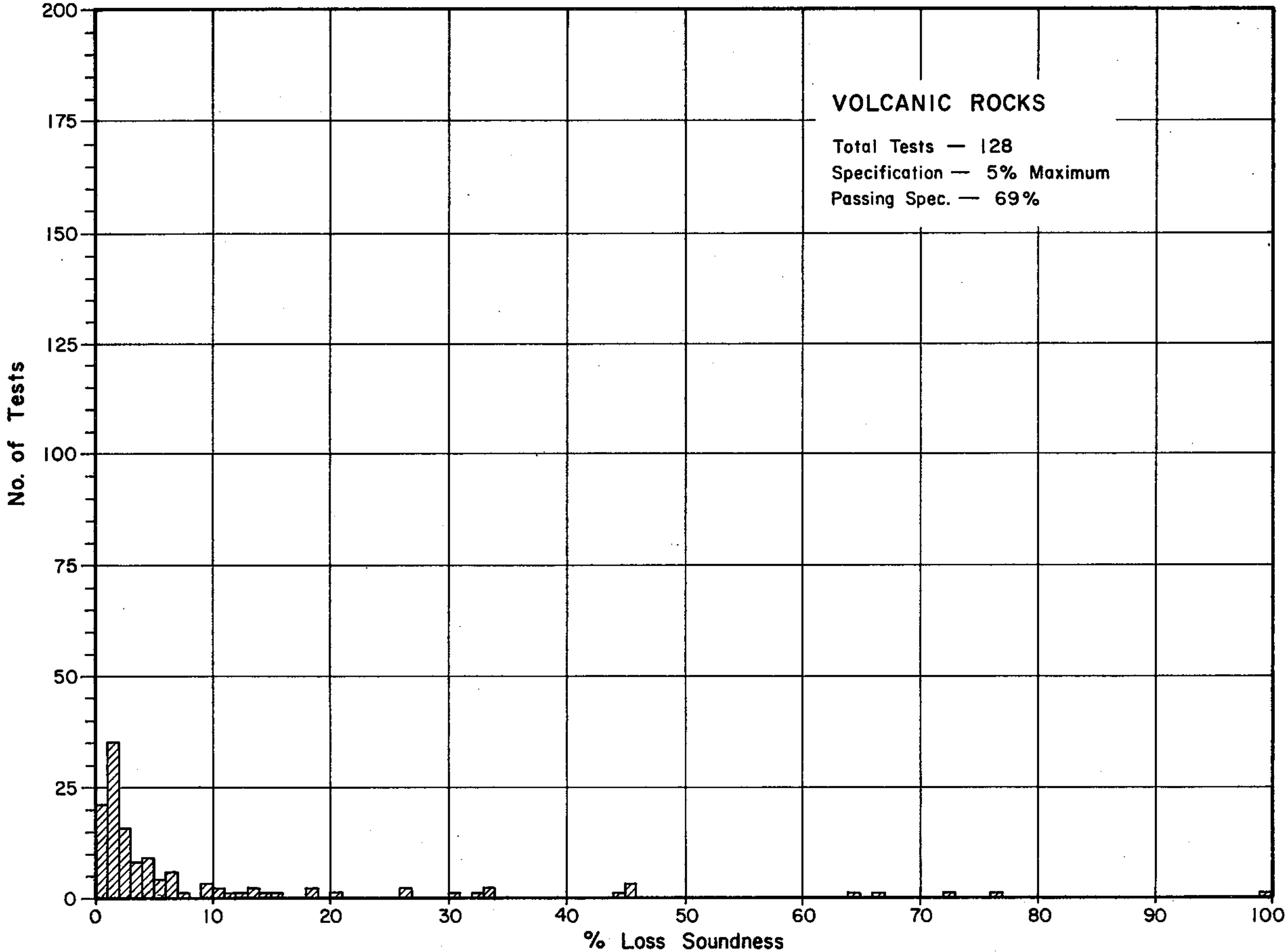

Figure 17.–Distribution of Soundness test results

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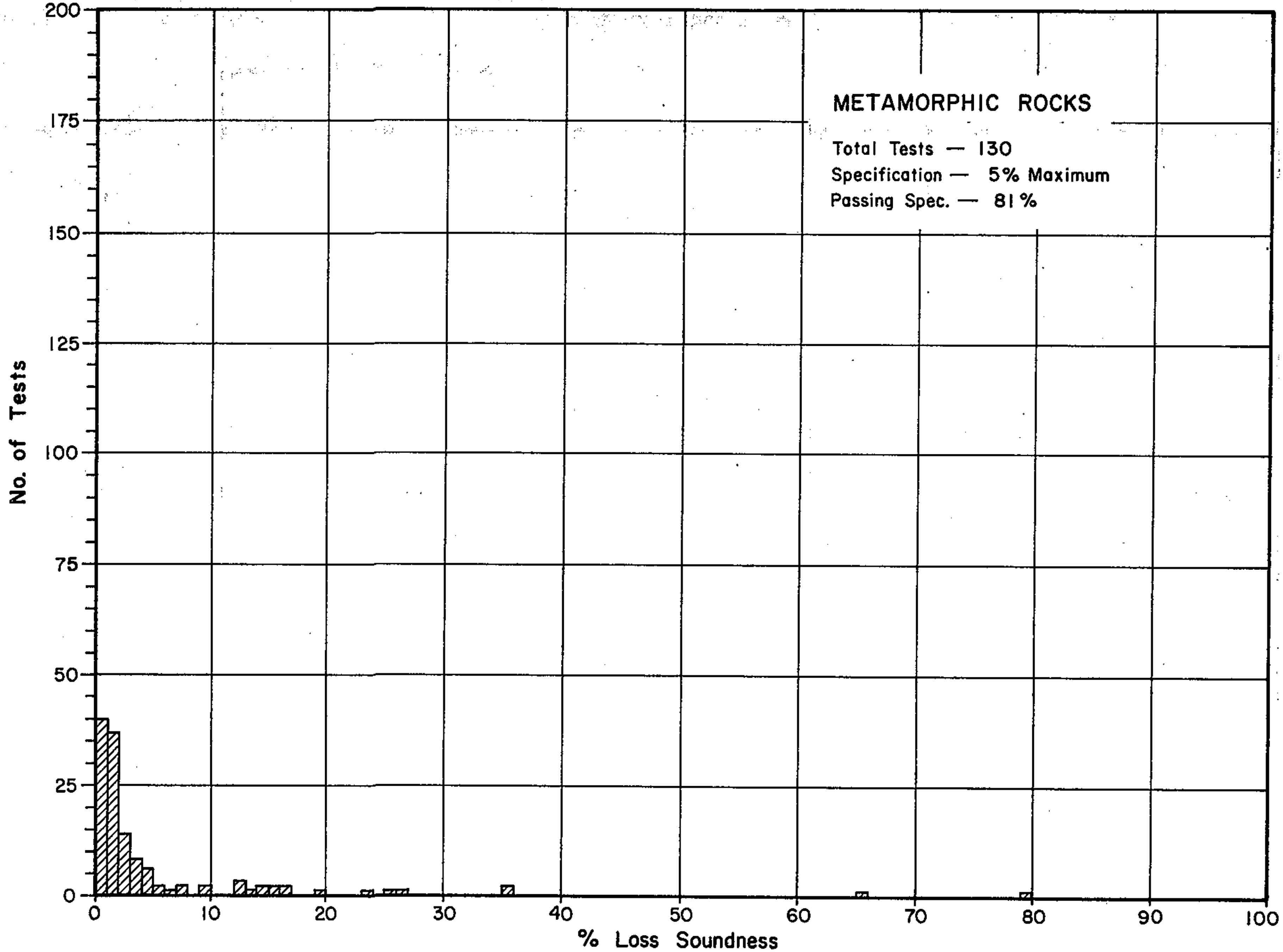

Figure 18 - Distribution of Soundness test results

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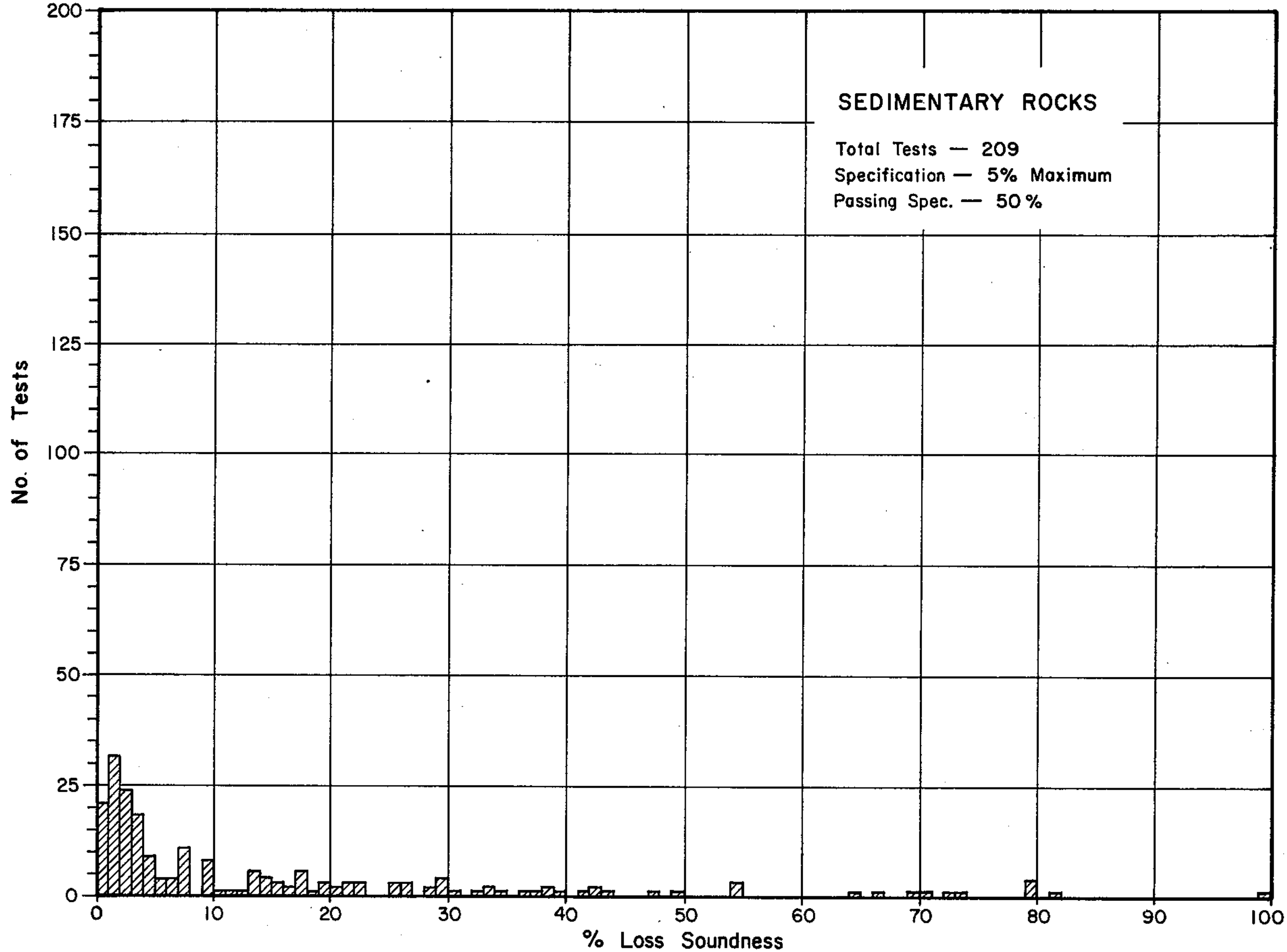

Figure 19.-Distribution of Soundness test results

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Table 9.-Regular and Cube Soundness Test Results

Sample No.	Percent Loss Regular	Percent Loss Cube
61-1671	1.6	25.2
4484	1.4	0.0
4603	22.5	0.4
4682	13.4	0.1
4744	4.3	16.5
5328A	10.9	9.6
5328B	10.9	1.2
5331A	0.8	0.4
5331B	0.8	0.2
5331C	0.8	17.0
5332A	0.7	0.0
5332B	0.7	0.0
5332C	0.7	0.0
62-1191	13.6	0.8
2029	25.0	0.0
2030A	2.5	0.0
2030B	2.5	3.9
2190	2.1	0.0
2366	1.4	0.0
2517	3.2	66.1
3080	1.4	0.0
3081A	1.4	0.1
3081B	1.4	0.2
3925A	2.2	0.0
3925B	2.2	0.3
4019	1.2	0.0
4399	1.3	0.0
4418	4.0	0.0
4477	2.0	0.0
4510A	2.4	0.0
4510B	2.4	0.0
5025	9.0	6.8
5154	1.5	2.2
5641A	3.1	0.0
5641B	3.1	0.0
5641C	3.1	0.0
5642	11.2	4.3
5830A	7.4	91.3
5830B	7.4	89.4

Sample No.	Percent Loss Regular	Percent Loss Cube
63-1148A	1.3	0.0
1148B	1.3	5.7
1148C	1.3	0.0
1587A	5.2	16.5
1587B	5.2	23.7
1587C	5.2	17.7
1587D	5.2	66.4
1588A	13.5	1.8
1588B	13.5	0.7
1588C	13.5	0.7
1588D	13.5	1.1
1589A	12.5	22.4
1589B	12.5	27.3
1635	9.9	6.5
1969	5.9	0.2
2231	0.2	0.0
2291	1.1	0.0
2293	4.4	0.4
2434	1.5	0.0
2598	3.2	7.0
2748	5.7	0.0
2749	32.5	0.4
2834	1.1	0.0
2963	1.2	0.0
3683	0.6	0.0
3745	1.2	0.0
3972	0.7	0.0
3973	16.2	0.0
4419	0.8	0.0
5018B	3.9	0.5
5018C	44.2	2.2
5018D	20.8	0.5
64-1002	1.6	5.4
1133	0.8	0.0
1361A	19.0	57.6
1361B	19.0	0.0
1379	26.1	100.0
1571	1.3	0.0
1572	0.9	0.0

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Table 9.-Regular and Cube Soundness Test Results-Continued

Sample No.	Percent Loss Regular	Percent Loss Cube	Sample No.	Percent Loss Regular	Percent Loss Cube
64-1659	11.7	0.0	64-3157	0.6	0.0
1691A	2.7	0.0	3240	0.5	0.0
1691B	2.7	0.0	3241	0.4	0.0
1691C	2.7	0.0	3483	1.6	0.5
1715A	0.7	0.0	3485	18.2	0.3
1715B	0.7	0.0	3486	1.5	0.0
1715C	0.7	0.0	3487	1.7	0.0
1716	0.6	0.0	3488	3.7	0.0
1725	1.4	0.0	3769	0.5	0.0
1737	0.2	0.0	4289	0.7	2.3
1788	3.9	0.0	4379	1.0	0.0
1950	0.3	1.3	4380A	0.8	0.0
2001A	3.2	29.1	4380B	0.8	0.9
2001B	3.2	58.2	4381	2.1	37.0
2059	1.6	0.0	4382	2.4	0.0
2060	8.8	1.6	4383	1.6	0.0
2061	1.0	0.0	4384	2.7	0.0
2062	9.7	1.9	4385	54.7	2.4
2064	4.4	0.0	4664	10.9	0.0
2065	21.8	1.3	4665	17.7	0.0
2066	3.6	0.0	4666	45.5	8.2
2067	4.0	0.1	4667	4.9	0.0
2068	0.9	36.1	4668	8.7	0.0
2285	1.1	1.5	4700	1.9	0.0
2286	3.5	1.4	4800	5.5	0.4
2475	1.3	0.2	4837	2.6	2.5
2793	8.6	0.0	4838	1.4	0.0
2941	1.5	0.0	5006	1.9	2.8
3026A	22.1	0.0	5062	1.0	0.0
3026B	22.1	0.0	5248	3.5	0.0
3026C	22.1	0.0	5249	5.4	0.4

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APPENDIX D

Los Angeles Rattler Test

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Table 10.-Fifteen of 622 Samples That Failed Only The LART Specification Test

% Loss in LART	Rock Type	Remarks
45.4	Granitic	-
47.8	"	-
48.4	"	-
48.8	"	-
49.0	"	Slightly weathered
51.6	"	Installation. Good rock
52.0	"	" " "
57.2	"	" " "
59.4	"	"
60.0	"	" Good rock
60.4	"	" "
57.0	Andesite	-
51.0	Calc. ss	Installation. Slightly weathered
51.0	Dolomite	-
54.0	"	-

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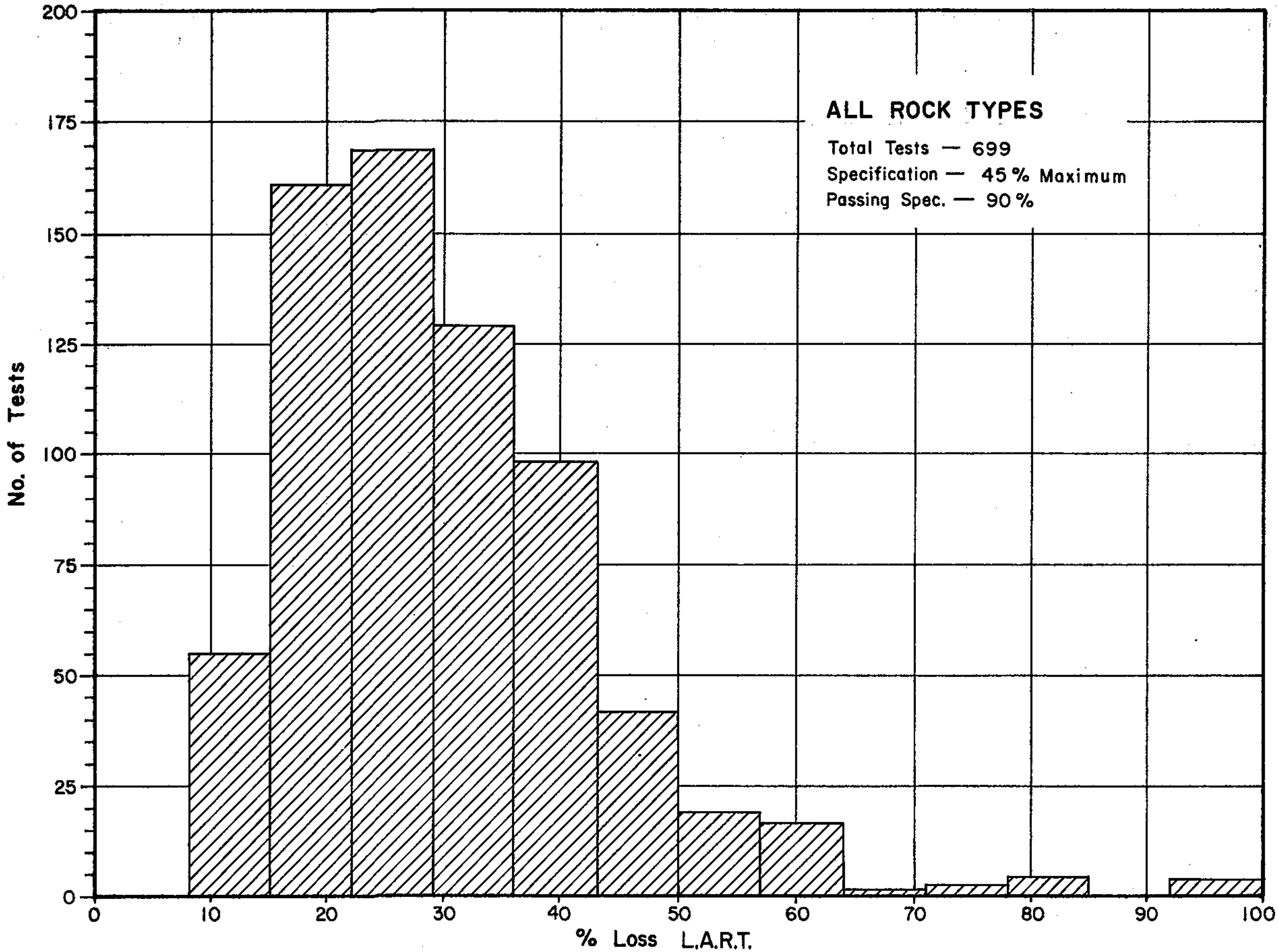

Figure 20.-Distribution of L.A.R.T. test results

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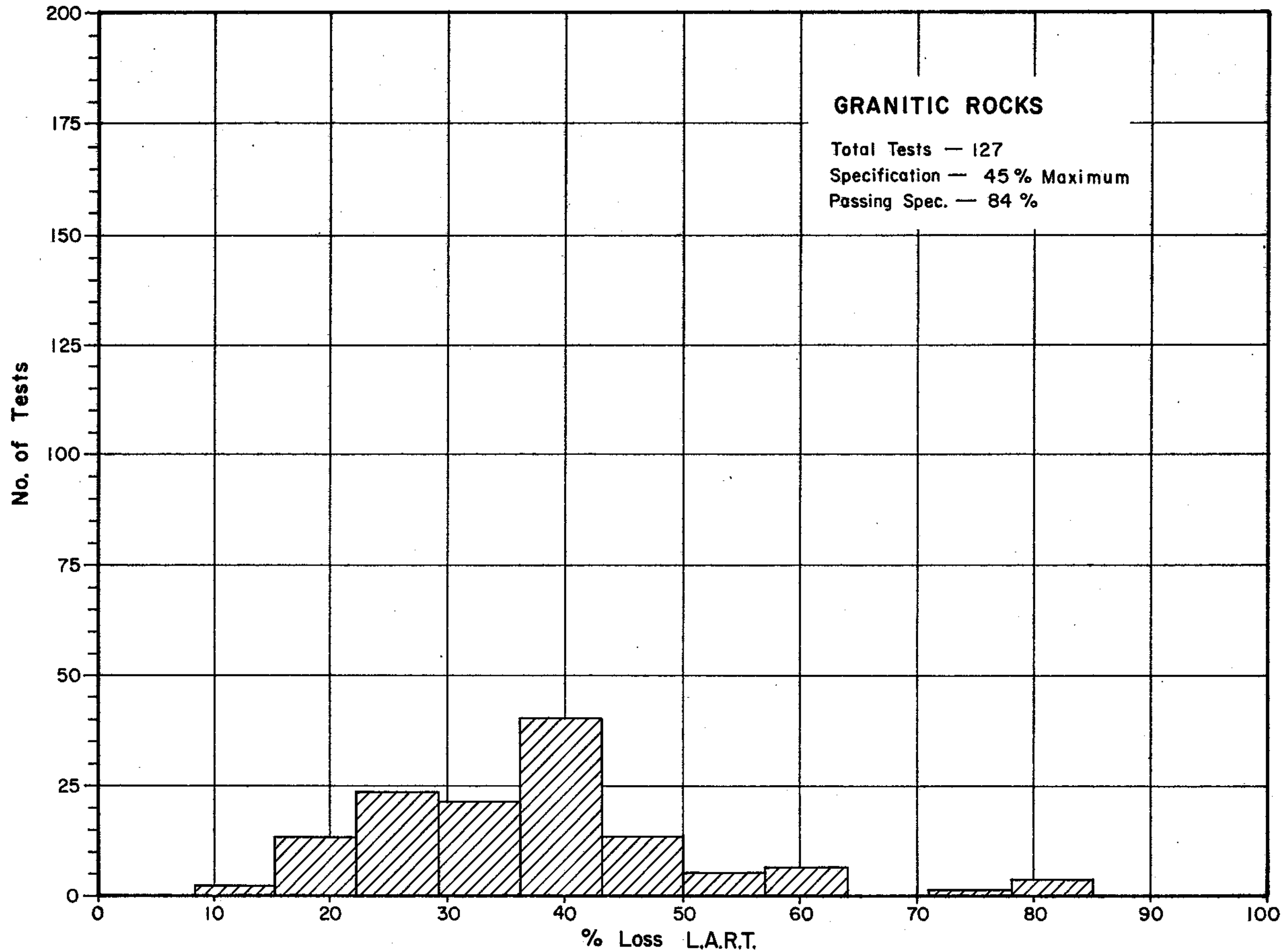

Figure 21.-Distribution of L.A.R.T. test results

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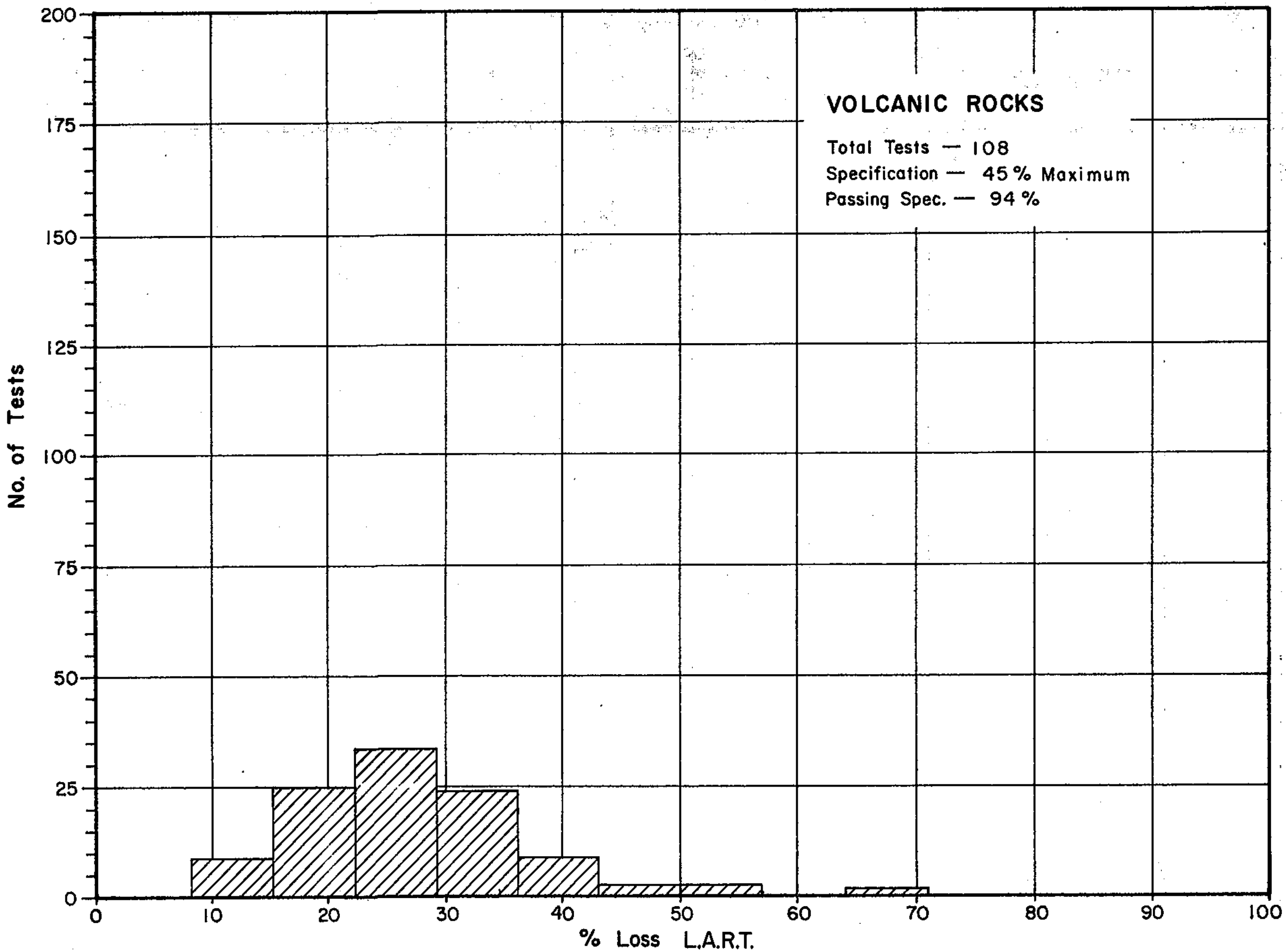

Figure 22.-Distribution of L.A.R.T. test results

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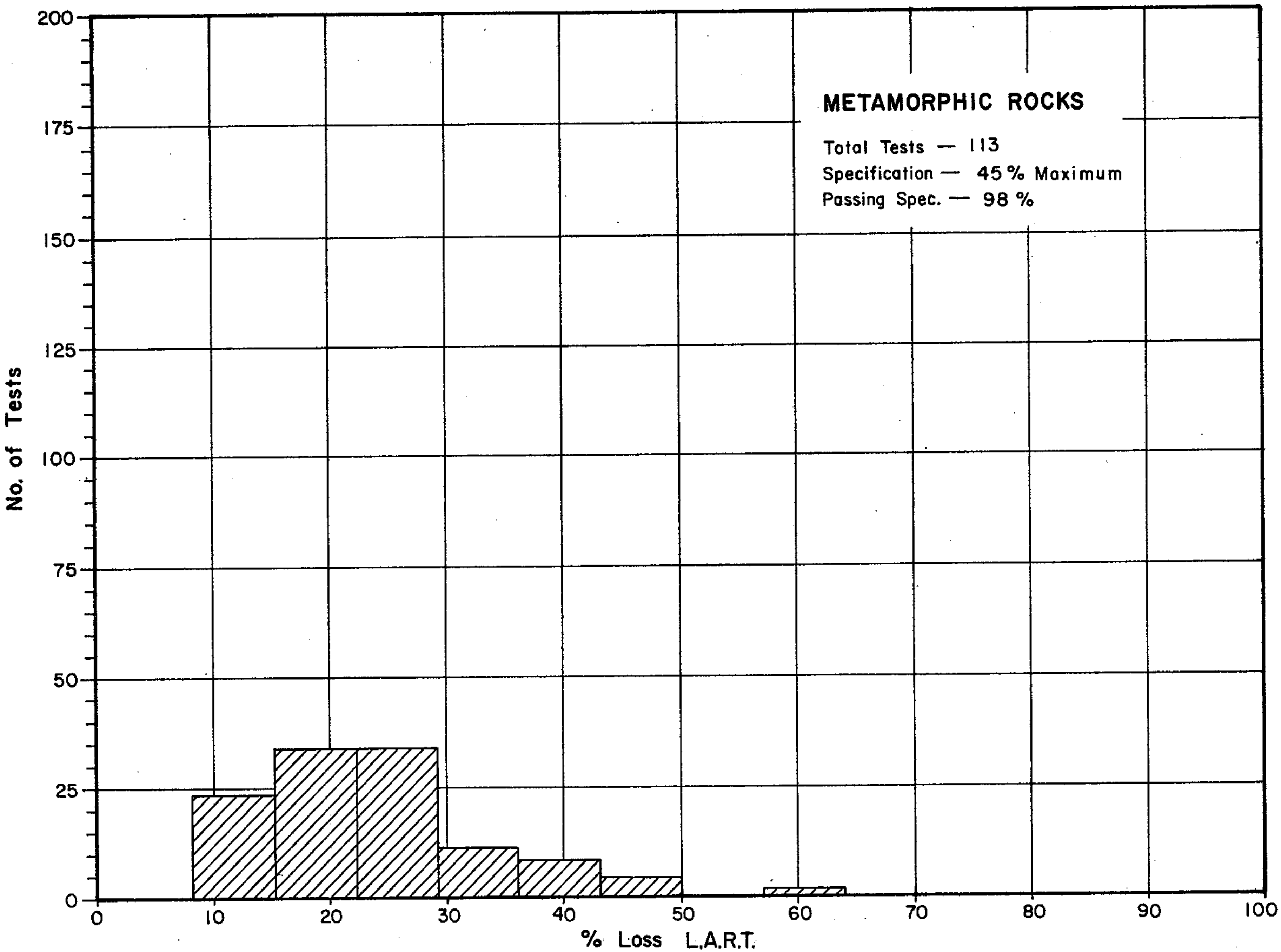

Figure 23.-Distribution of L.A.R.T. test results

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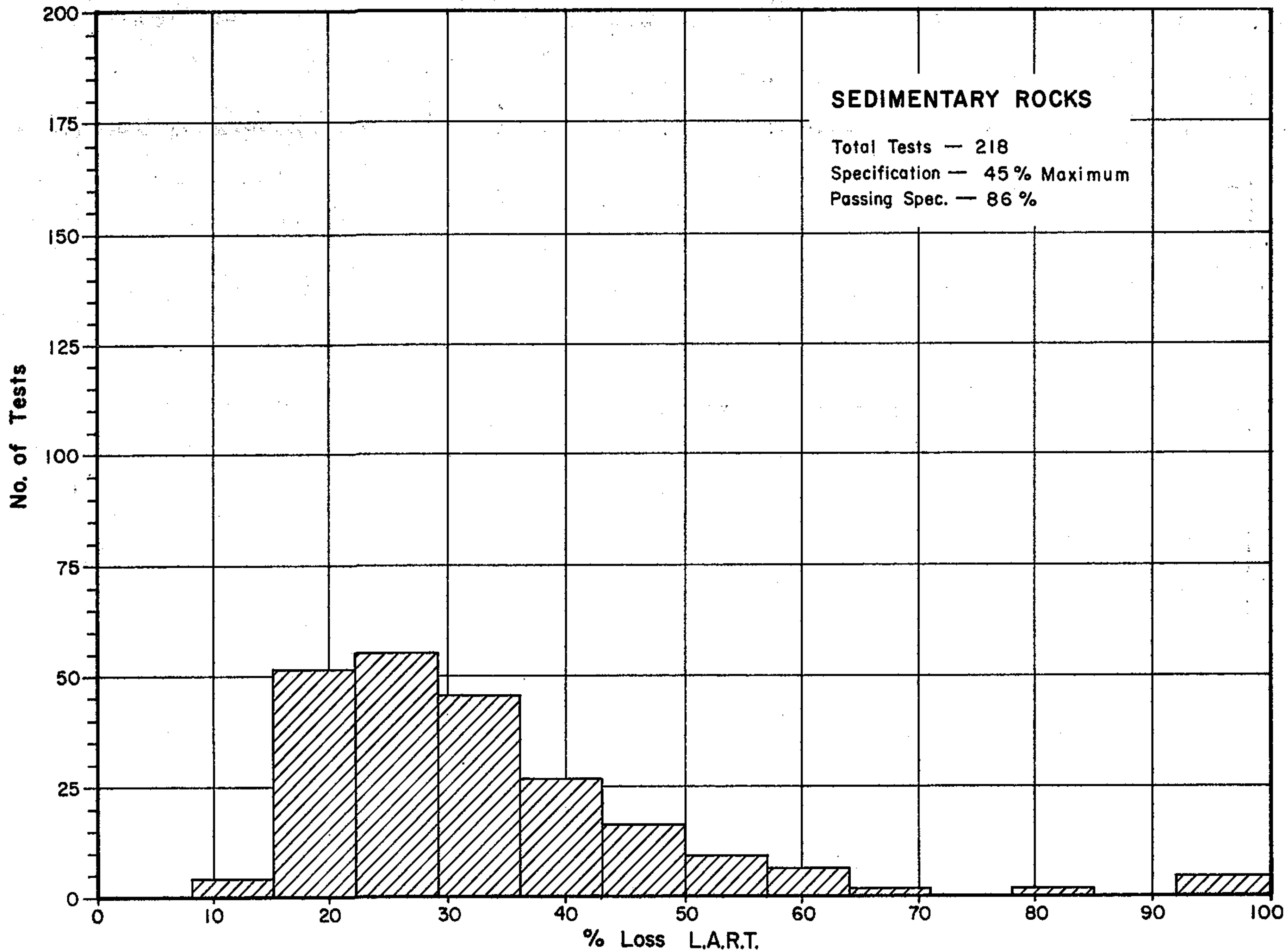

Figure 24.-Distribution of L.A.R.T. test results

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APPENDIX E

Apparent Specific Gravity

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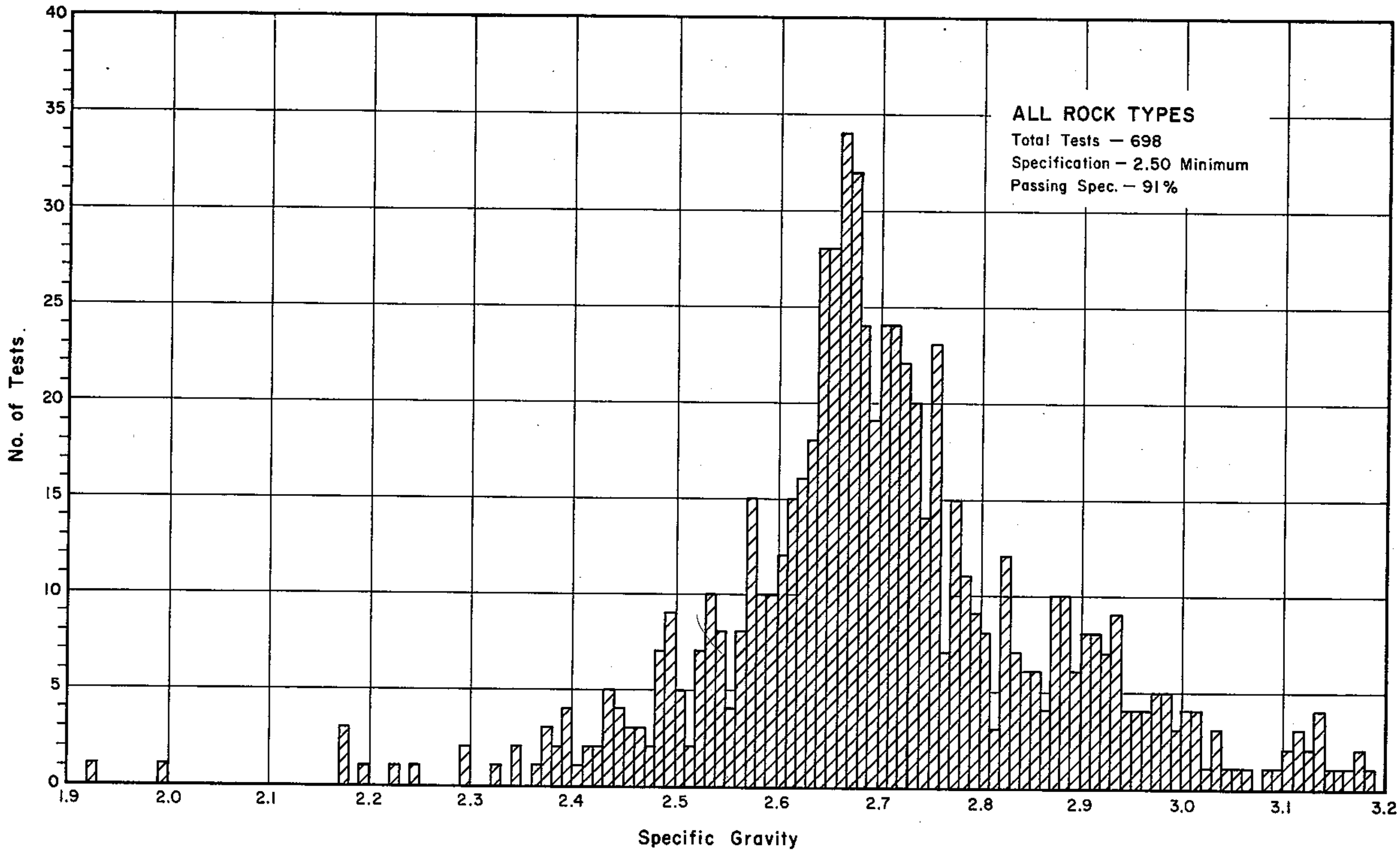

Figure 25.-Distribution of Specific Gravity test results

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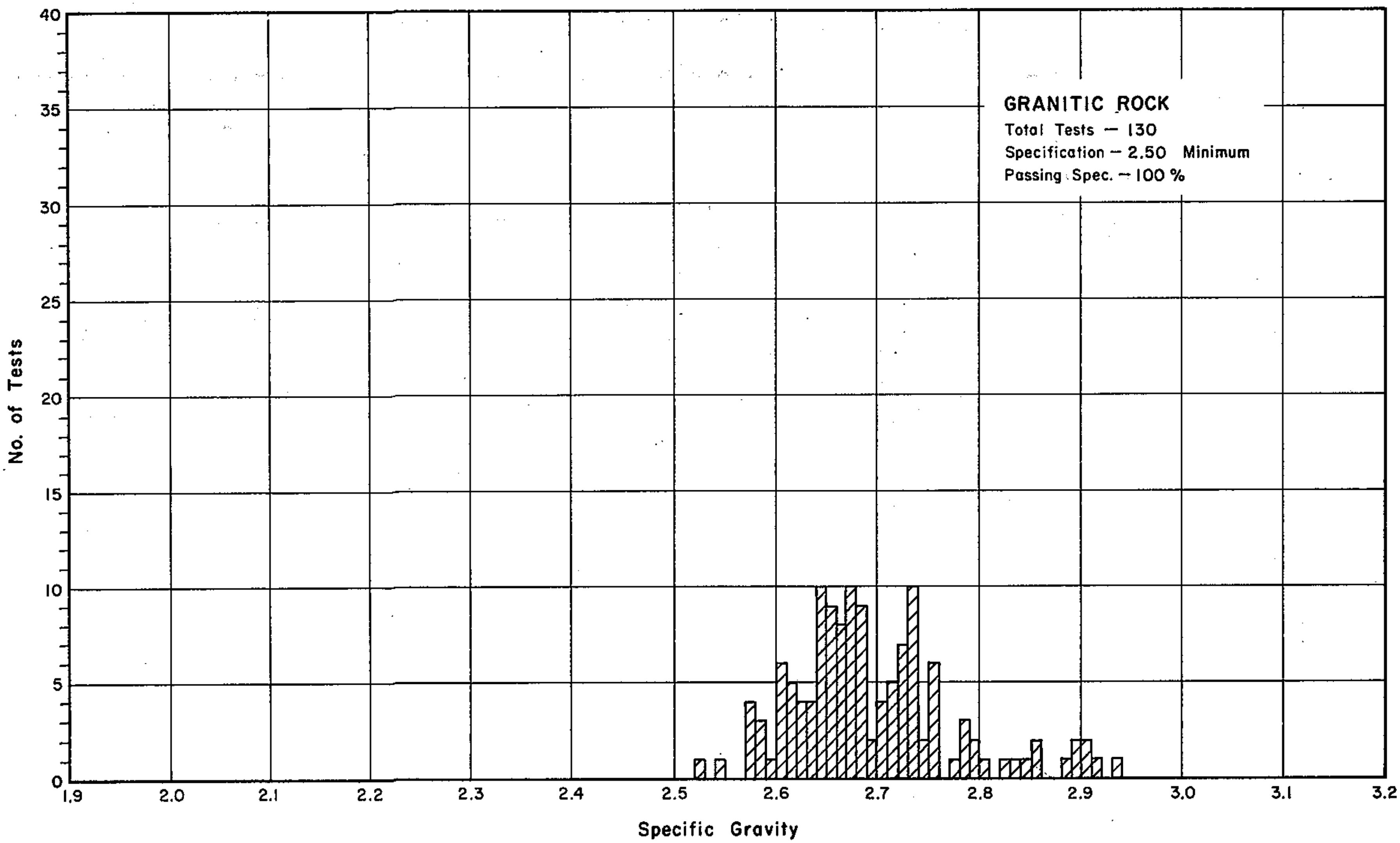

Figure 26.- Distribution of Specific Gravity test results

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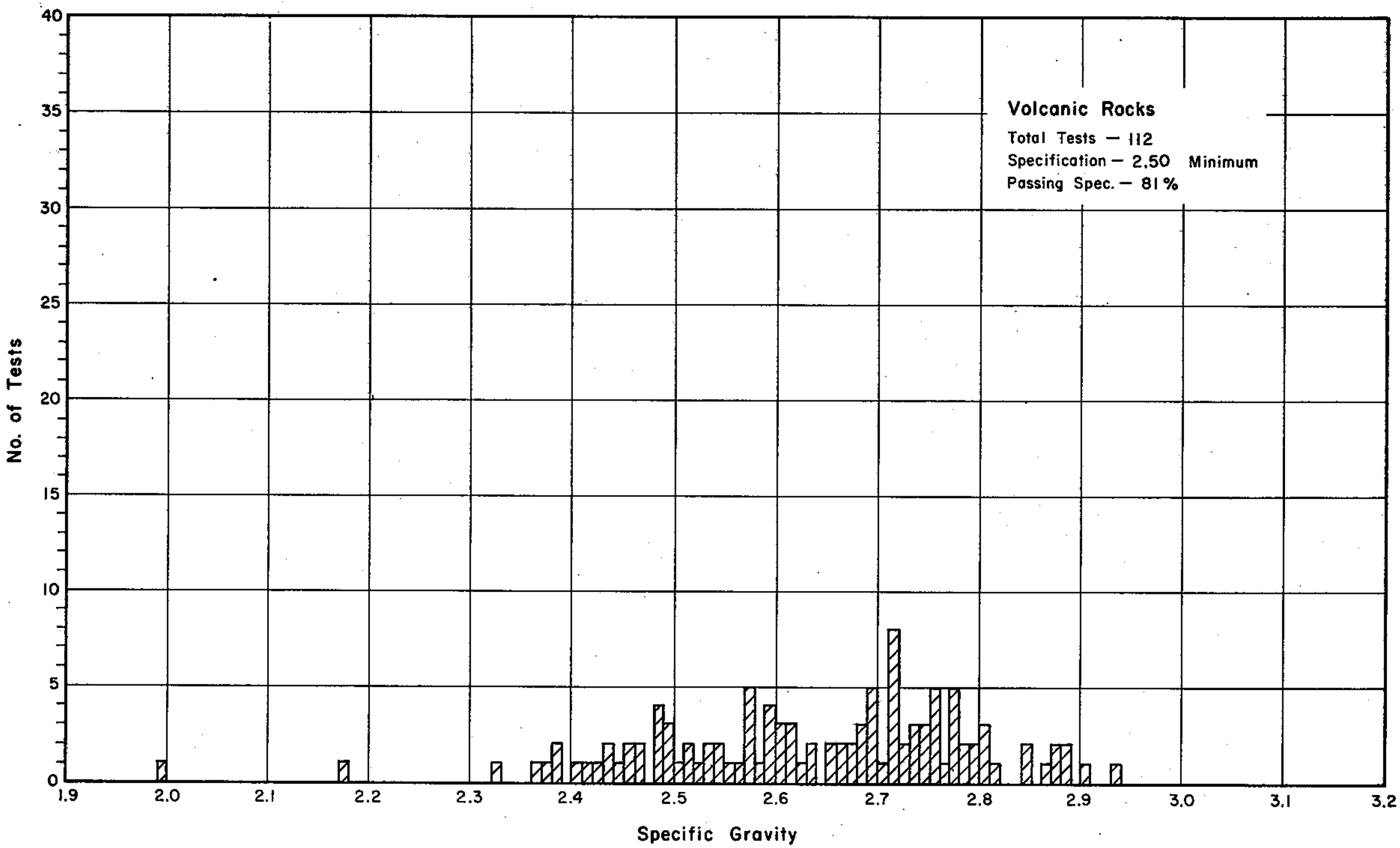

Figure 27.-Distribution of Specific Gravity test results

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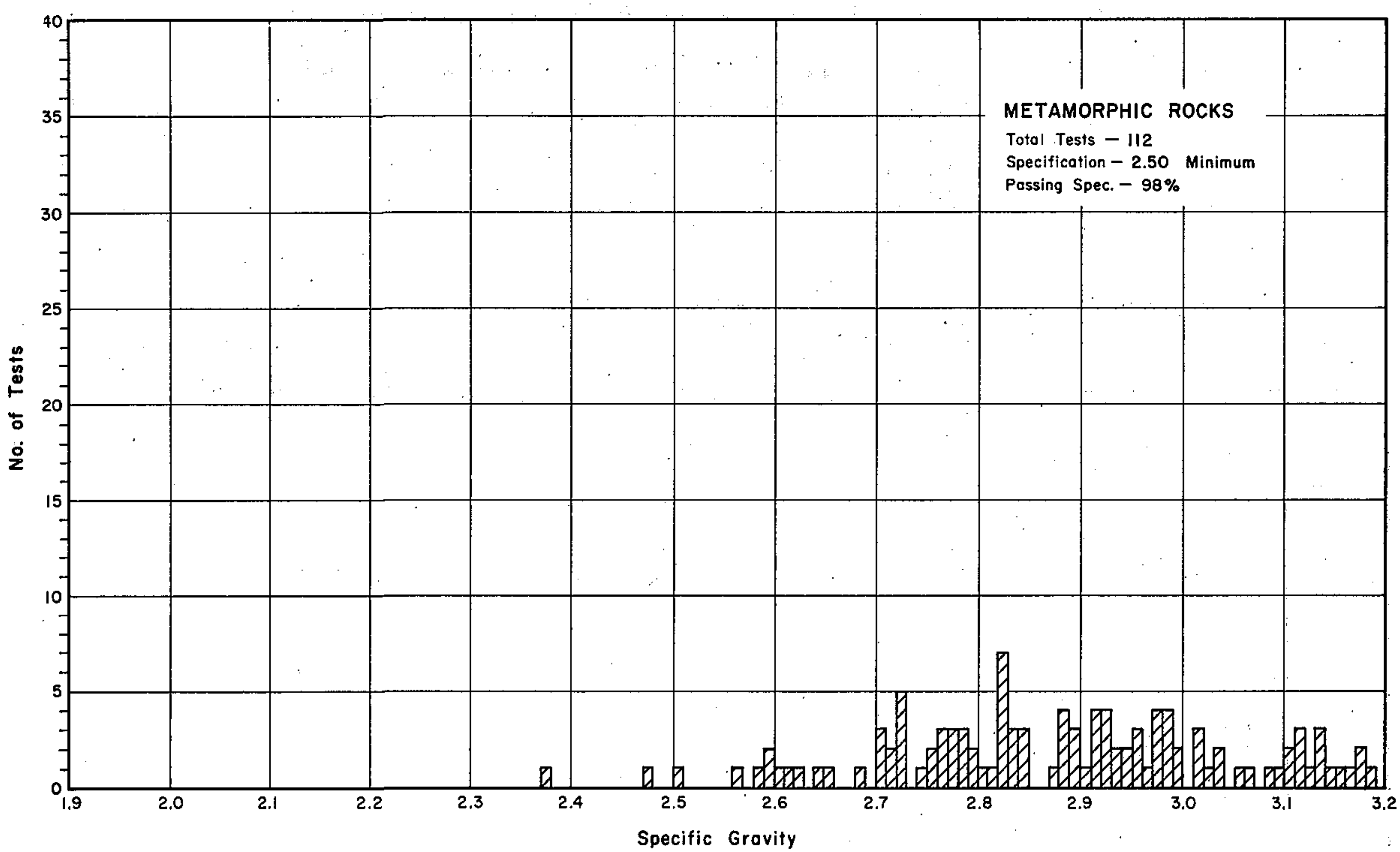

Figure 28.-Distribution of Specific Gravity test results

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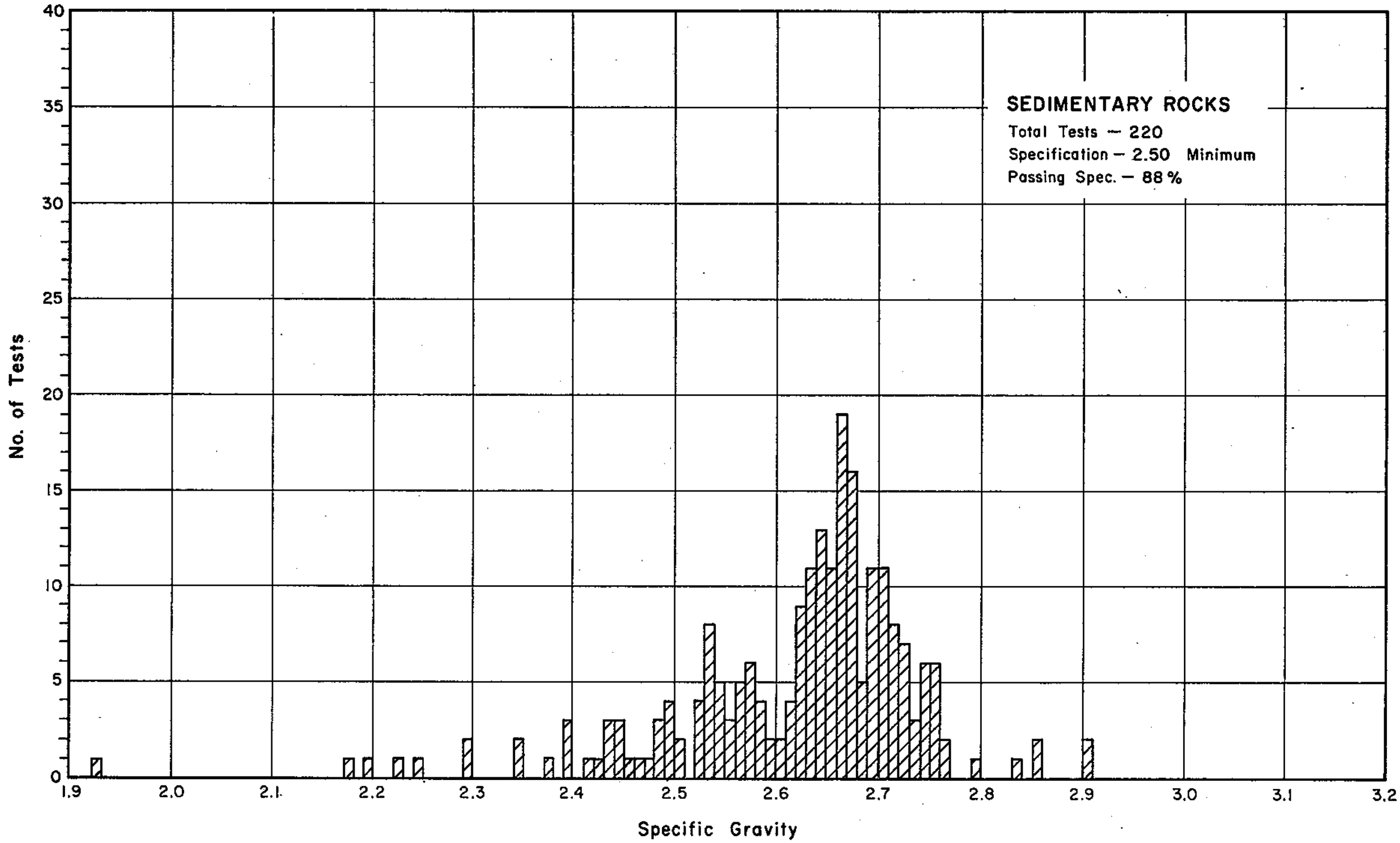

Figure 29.–Distribution of Specific Gravity test results

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APPENDIX F

Absorption

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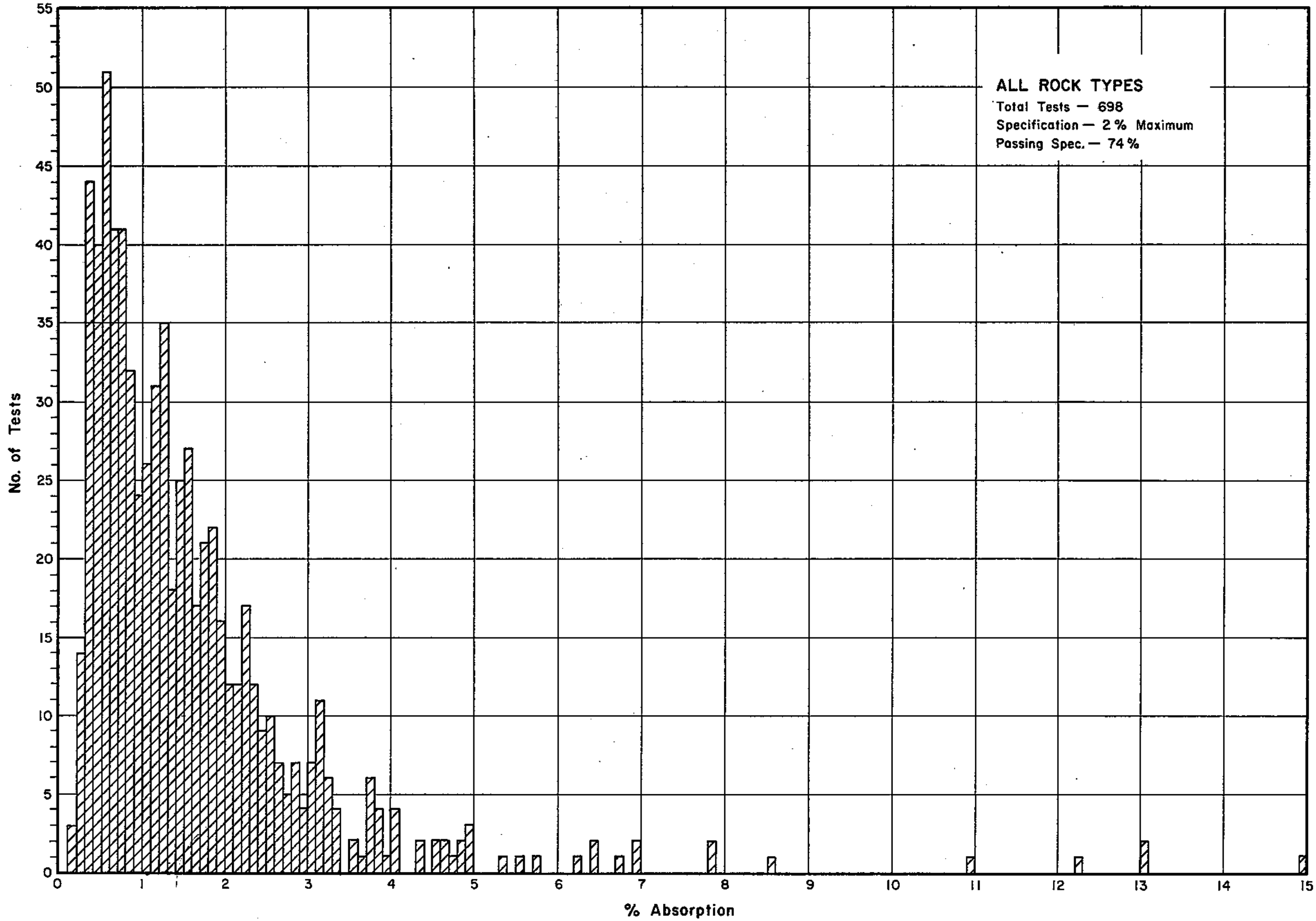

Figure 30.-Distribution of Absorption test results

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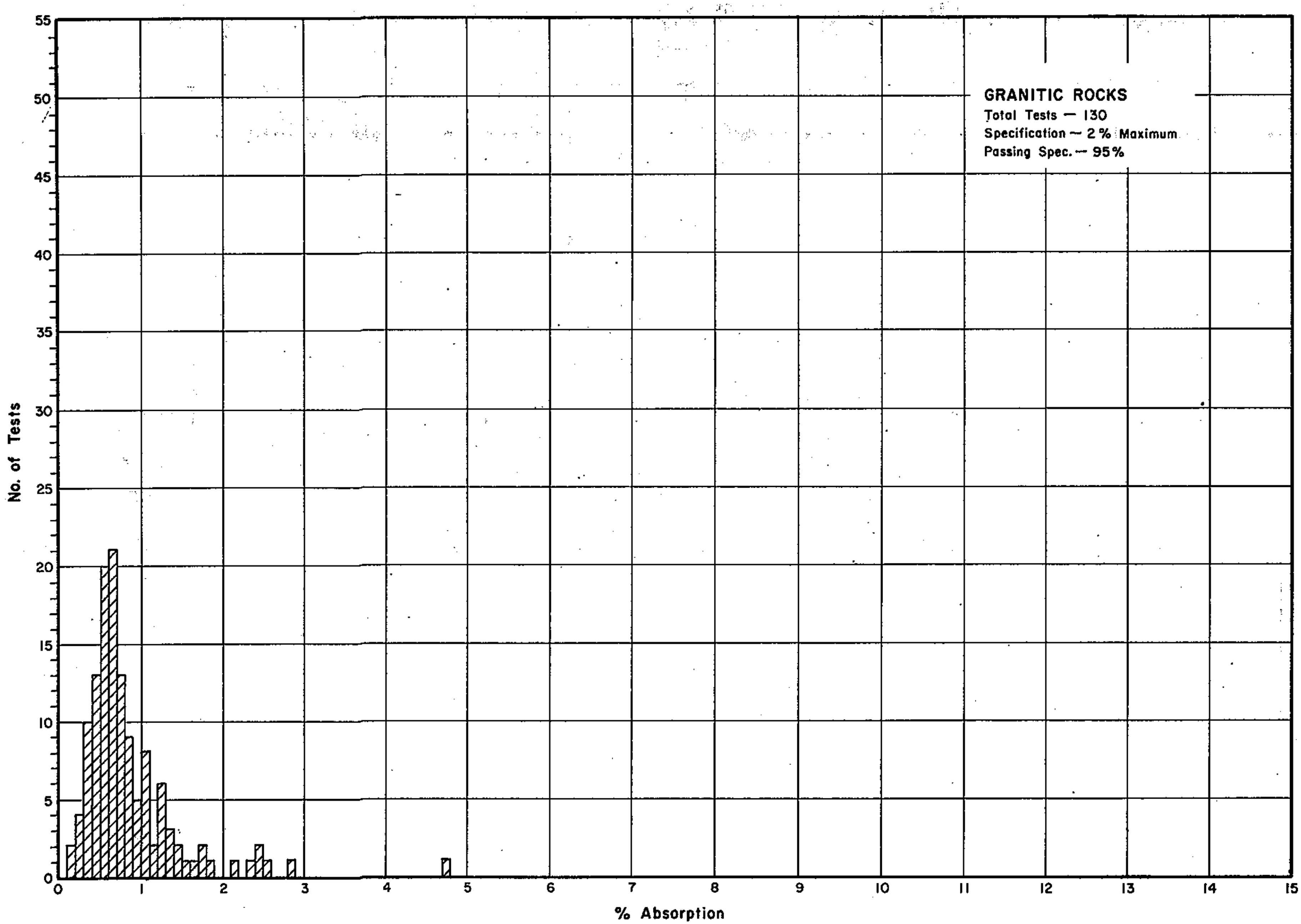

Figure 31.-Distribution of Absorption test results

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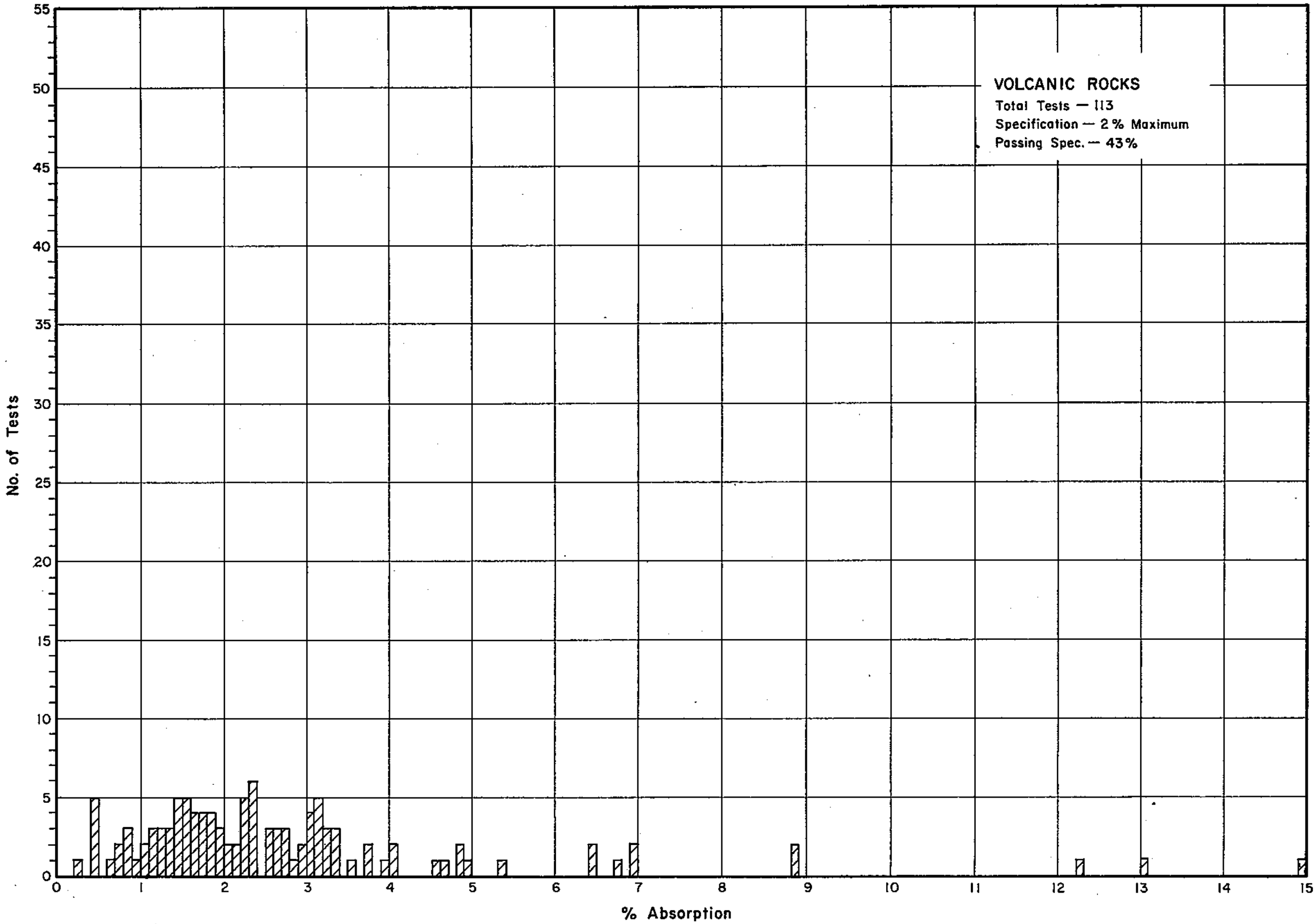

Figure 32.-Distribution of Absorption test results

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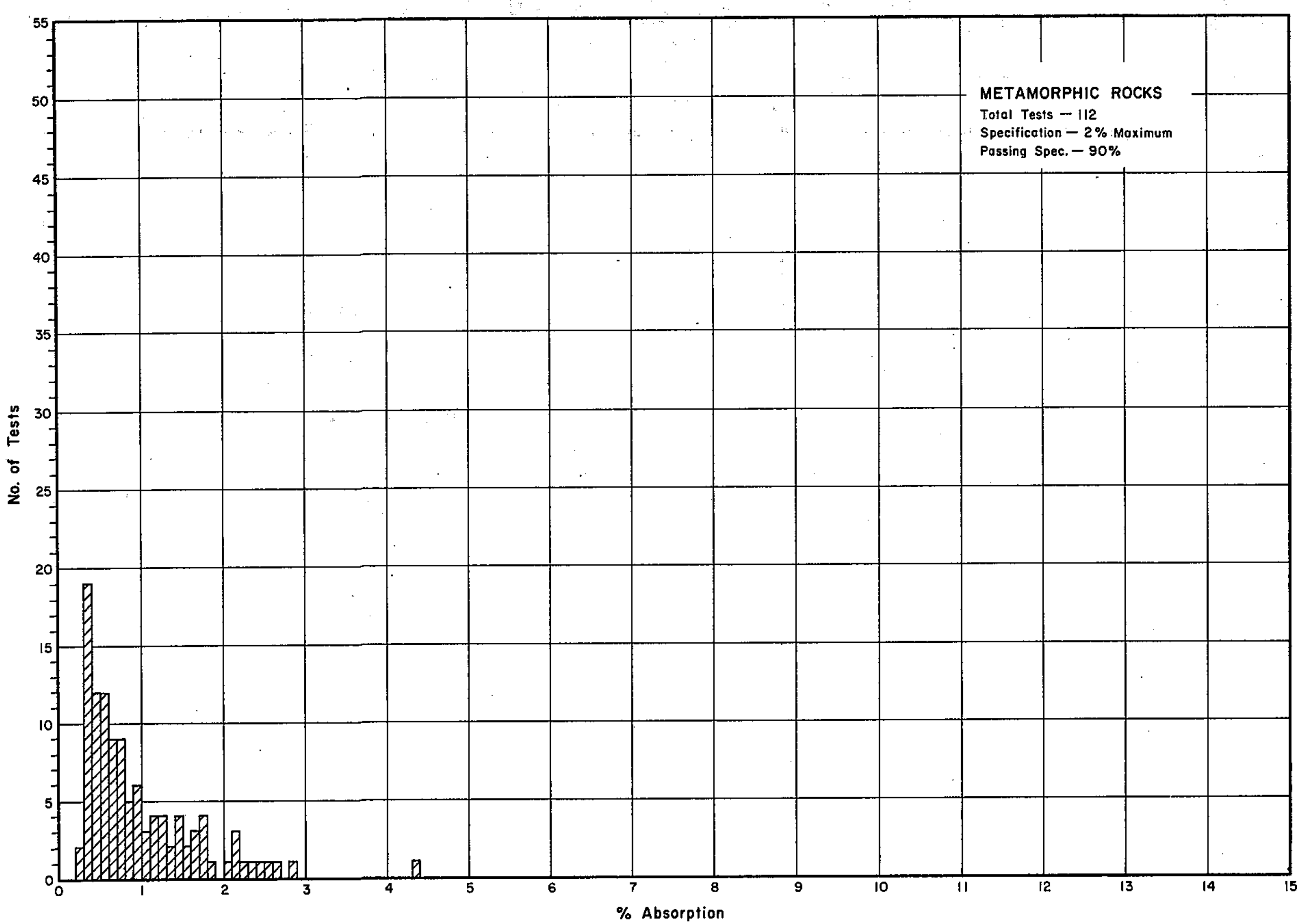

Figure 33.-Distribution of Absorption test results

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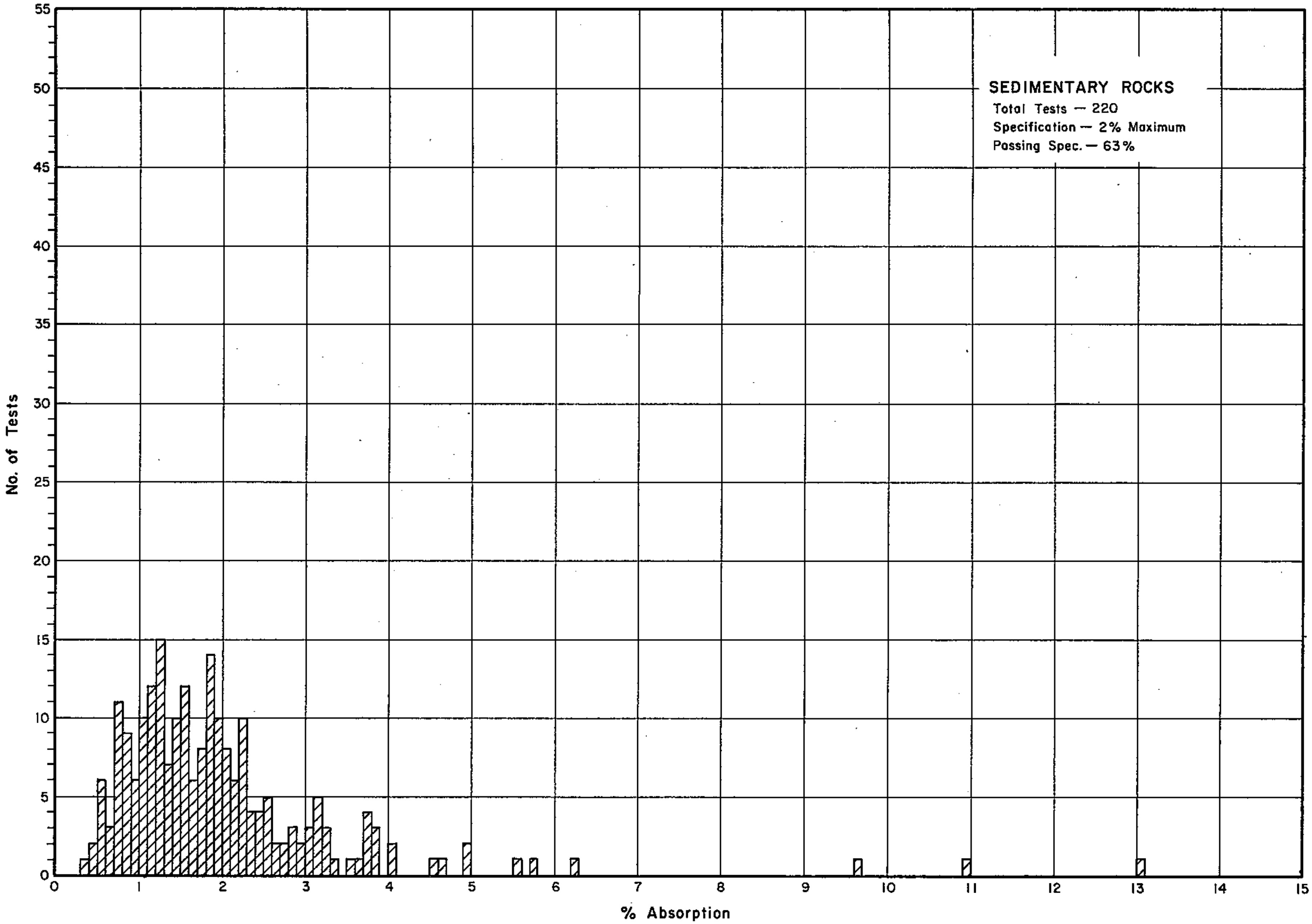

Figure 34.-Distribution of Absorption test results

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APPENDIX G

Durability

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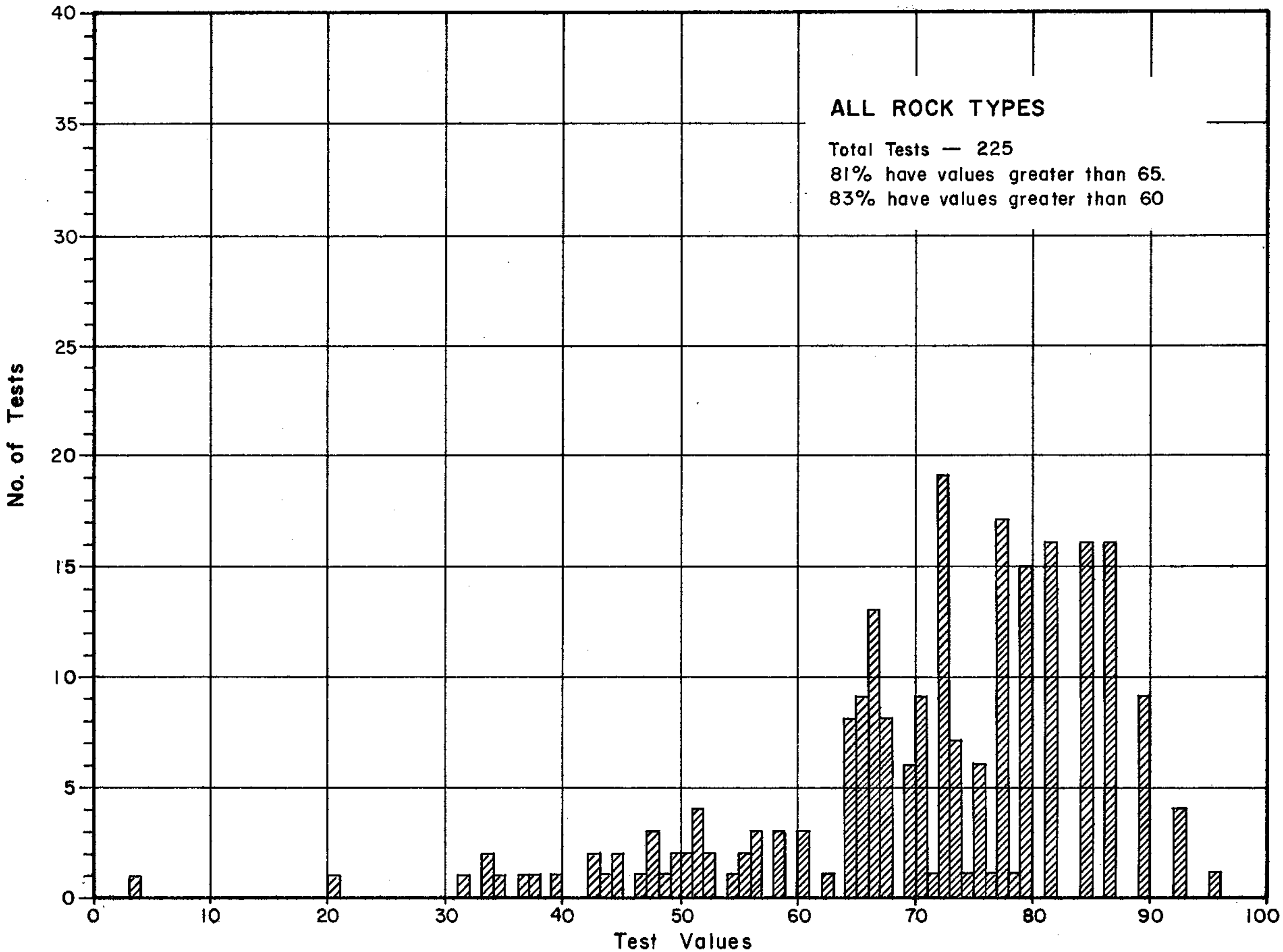

Figure 35 – Distribution of Durability test results

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APPENDIX H

Wet-Dry Test

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Table 11.-Wet-Dry Test Results for Fresh Water and Sea Water

Sample Number	Sample Source	Sample Type	Fresh Water % Loss	Sea Water % Loss
-	Rocklin	Quartz diorite	0.2	0.1
64-2067	Waddell Bluffs	" "	4.9	1.0
2068	" "	" "	0.7	0.4
4381	Nicasio Reservoir	Olivine gabbro	0.0	0.0
4666	Emeryville	Andesite	2.4	0.0
4667	Richmond	Sandstone	3.6	2.1
"	"	"	6.1	5.0
"	"	"	6.7	5.3
65-1870	Aliso Canyon	"	0.5	0.4
1871	Bazzi	Limestone	0.5	0.3
1872	Hollister	Dolomite	0.9	0.7
1874	Ricioli	Glaucophane schist	0.8	0.7
1875	Crawford	Limestone	0.8	0.4
1876	Chimney Canyon	Sandstone	0.8	0.6

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Table 12.-Wet-Dry Test Results for Fresh Water

Sample Number	Sample Source	Sample Type	Fresh Water % Loss
64-2059	Rincon Point	Sandstone	0.6
2060	" "	"	0.6
2062	Point Mugu	"	1.0
2064	" "	Diabase	1.0
2065	" "	Siltstone	0.9
3483	North Yuba River Bridge	Schist	0.3
3484	Cave Rock, Lake Tahoe	Dacite	1.0
3485	" " " "	"	0.8
3486	Flycasters Bend	Vesicular olivine basalt	0.4
3487	" "	Olivine basalt	0.3
3488	Squaw Creek	Tuff	0.8
65-3187	Big River Bridge	Sandstone	2.8
66-1573	Needles	Metadiorite	0.2
1574	Halloran	Basalt	0.4
1652	Pudding Creek	Sandstone	0.3
1653	" "	"	0.6

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Table 13.-Wet-Dry Test Results for Various Sizes of Crushed Particles

Sample Number	Sample Source	Sample Type	% Loss				
			1½"x1"	1"x3/4"	3/4"x½"	½"x3/8"	3/8"x#4
65-3187	Big River Bridge	Sandstone	1.6	2.8	2.3	3.0	6.3
3612	Alder Creek	Sandstone	0.4	-	-	-	1.0
3937	Larson Quarry	Limestone	1.0	-	1.4	-	2.8
4293	Cohasset Rd.	Basaltic andesite	0.6	-	-	-	0.4
66-1573	Needles	Metadiorite	-	0.2	-	-	0.3
1574	Halloran Summit	Basalt	-	0.4	-	-	0.5
1652	Pudding Creek	Sandstone	-	0.3	-	-	0.5
1653	Pudding Creek	Sandstone	-	0.6	-	-	0.8

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APPENDIX I

Freeze-Thaw Test

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Table 14.-Freeze-Thaw Test Results

Sample Number	Sample Source	Sample Type	% Loss
	Pillar Point	Sandstone	0.2
	Yuba Pass	Quartz monzonite	0.0
	Rocklin	Quartz diorite	0.0
64-2059	Rincon Point	Sandstone	0.0
2060	" "	"	0.0
2062	Point Mugu	"	0.0
2064	" "	Chloritized diabase	0.0
2065	" "	Metasandstone	0.0
2066	Waddell Bluffs	Quartz diorite	0.0
2067	" "	" "	17.9
2068	" "	" "	0.7
3240	Parks Bar	Andesite	0.0
3241	Spring Valley Road	Hornblende andesite	0.0
3484	Cave Rock, Lake Tahoe	Dacite	0.0
3483	North Yuba River Bridge	Schist	0.0
3485	Cave Rock, Lake Tahoe	Dacite	0.0
3486	Flycasters Bend	Vesicular olivine basalt	0.0
3487	" "	Olivine basalt	0.0
3488	Squaw Creek	Tuff	0.0
4379	Brooks	Basalt	0.7
4380	Camp Meeker	Schist	0.0
4380 u	" "	Ultrabasic	0.3
4381	Nicasio Reservoir	Olivine gabbro	0.5
4381	" "	" "	1.4 Immersed

Table 14.-Freeze-Thaw Test Results-Continued

Sample Number	Sample Source	Sample Type	% Loss
64-4382	Nicasio Reservoir	Olivine gabbro	0.6
4383	Bolinas Bay	Sandstone	1.7
4384	Tocaloma Bridge	"	0.3
4385	Duncan Mills	"	100.0
4664	Aromas	Quartz diorite	0.1
4665	Davenport	Sandstone	0.3
4666	Emeryville	Andesite	1.8
4668	Waddell Bluffs	Quartz diorite	12.3
4668	" "	" "	35.2 Immersed
4800	Camp Meeker	Schistose ultrabasic	7.1
4837	" "	Ultrabasic	0.7

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APPENDIX J

Rapid Abrasion Test

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Table 15.-Rapid Abrasion Test Results

Sample Number	Sample Source	Sample Type	% Loss
64-4383	Bolinas Bay	Sandstone	7.6
4384	Tocaloma Bridge	Sandstone	11.8
4664	Logan Quarry	Quartz diorite	14.5
65-1870	Aliso Quarry	Sandstone	10.2
1871	Bazzi	Limestone	10.7
1872	Hollister Quarry	Dolomite	18.7
1873	Johnson	Sandstone	22.2
1874	Ricioli	Glaucophane schist	17.1
1875	Crawford Quarry	Limestone	16.0
1876	Chimney Canyon Quarry	Calcareous sandstone	10.4
1946	Oroville	Ultrabasic	11.3
2204	Horse Creek Bridge at Terminous Reservoir	Hornblende biotite granodiorite	11.2
2205	Caliente Creek Bridge	Biotite hornblende quartz diorite	11.3
2219	Kern River Canyon	Hornblende biotite quartz diorite	7.9
2220	Wartham Creek	Sandstone	34.6
2221	French Gulch at Lake Isabella	Granodiorite	10.5
2712	Woodfords	Granodiorite	9.9
2713	Rte. 4 West of Monitor Pass Jct.	Silicified tuff	2.8
2714	Near Hangmans Bridge, Markleeville	Tuff	24.7
2715	Angel's Camp	Greenschist	15.1
2716	Coulterville	Mariposite	9.2
2717	Mariposa	Metagabbro	9.2
2718	Merced River near El Portal	Slate and Slaty Rock	10.7
2719	Jackson	Diorite	9.6
3187	Big River Bridge at Mendocino	Sandstone	18.9

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Table 15.-Rapid Abrasion Test Results-Continued

Sample Number	Sample Source	Sample Type	% Loss
65-3188	DeHaven Creek Bridge	Sandstone	12.1
3189	Juan Creek Bridge	Sandstone	13.4
3190	2.2 mi. South of Longvale	Gaucophane schist	11.0
3191	2 mi. North of Kelseyville	Porphyritic andesite	8.9
3192	1 mi. North of Weott	Sandstone	14.4
3193	Red Mountain Creek	Sandstone	19.6
66-1570	Cottonwood Creek	Biotite quartz diorite	9.7
1571	Devils Canyon	Hornblende biotite quartz diorite	13.1
1572	Sandrock Road	Metaandesite	4.4
1573	Needles	Metadiorite (gneissic)	11.3
1574	Halloran	Basalt	9.8
1601	Big Sycamore	Calc-sandstone	20.7
1602	Ventura Beach S.P.	Andesite	10.5
1603	Morongo Valley	Biotite gneiss	17.6
1604	Meadowlark	Granite	4.0
1605	Temecula	Biotite quartz diorite	9.8
1606	Ventura Marina	Volcanic agglomerate	14.2
1607	Alberhill	Dacite porphyry	9.3
1608	Castaic Junction	Anorthosite	8.5
1615	Pudding Creek	Sandstone	23.5
1651	Coughborn Ranch	Sandstone	12.3
1652	Pudding Creek W.	Sandstone	21.3
1653	Pudding Creek	Sandstone	20.2
2459	Tehachapi Quarry	Limestone	19.1
2460	Walker River	Granite	14.5
2461	Virginia Creek	Dacite porphyry	15.4

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Table 15.-Rapid Abrasion Test Results-Continued

Sample Number	Sample Source	Sample Type	% Loss
66-2462	Bishop	Biotite granite	11.8
2463	Little Lake	Gneissic granite	13.1
2464	Salt Wells Canyon	Granodiorite	7.3
2465	Tehachapi	Quartz diorite	6.0
2581	Stone Corral Quarry	Sandstone	30.0
3101	No. Fork of Pitt River	Basalt	14.9
3102	Secret Valley Creek	Basalt	10.5
3103	Klamath River	Ultrabasic	11.3
3104	Helena	Schistose metagabbro	8.0
3367	Cave Rock	Dacite	9.8
3368	Flycasters Bend	Basalt	16.7
3369	Squaw Creek	Tuff	11.2

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